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Historical Review of Uncommanded Lateral-Directional Motions at Transonic Conditions

Joseph R. Chambers*
Ball Aerospace Systems Division, Fairborn, Ohio 45324-6269
and
Robert M. Hall†
NASA Langley Research Center, Hampton, Virginia 23681-2199

This paper presents the results of a survey of past experiences with uncommanded lateral-directional motions at transonic speeds during specific military aircraft programs. The effort was undertaken to provide qualitative and quantitative information on past airplane programs that might be of use to the participants in the joint NASA/Navy/Air Force Abrupt Wing Stall Program. The Abrupt Wing Stall (AWS) Program was initiated because of the experiences of the F/A-18E/F development program, during which unexpected, severe wing-drop motions were encountered by preproduction aircraft at transonic conditions. These motions were judged to be significantly degrading to the primary mission requirements of the aircraft. Although the problem was subsequently solved for the production version of the F/A-18E/F, a high-level review panel emphasized the poor understanding of such phenomena and issued a strong recommendation to "initiate a national research effort to thoroughly and systematically study the wing drop phenomena." A comprehensive, cooperative NASA/Navy/Air Force AWS Program was designed to respond to provide the required technology requirements. A work element was directed at a historical review of wing-drop experiences in past aircraft development programs at high subsonic and transonic speeds. In particular, information was requested regarding: specific aircraft configurations that exhibited uncommanded motions and the nature of the motions; geometric characteristics of the airplanes; flight conditions involved in occurrences; relevant data, including wind-tunnel, computational, and flight sources; figures of merit used for analyses; and approaches used to alleviate the problem. An attempt was also made to summarize some of the more important lessons learned from past experiences and to recommend specific research efforts.

Introduction

THE scope of the historical study was to survey past experiences for specific aircraft, generic studies, and fundamental research for information relevant to uncommanded lateral motions of high-performance aircraft at high subsonic and transonic speeds. The scope was expanded from the single phenomenon of wing drop to include other uncommanded lateral-directional motions, such as wing rock. This expanded scope appears to be appropriate in view of the serious shortcomings in the state of the art for general predictive capability and design methodology for transonic maneuvering conditions and the potential impact of undesirable lateral characteristics on mission effectiveness. This study identified numerous past aircraft development programs that encountered unpredicted deficiencies of this type during flight tests, requiring unforeseen additional analysis, flight tests, program delays, costs, and aircraft modifications.

The results of the study are intentionally limited to experiences with uncommanded motions at maneuvering angles of attack at transonic speeds and the aerodynamic factors related to transonic wing flow separation. Knowledge regarding uncommanded lateral-directional characteristics at low-speed, high-angle-of-attack conditions is readily available in the literature. Causal factors for such low-speed motions that have been documented include abrupt airfoil sectional stall characteristics; icing; power-induced effects (such as local flow angularity caused by propellers); and interacting vortical flows shed by forebodies or highly swept wings at high angles of attack. It is recognized that some approaches to flow separation control, such as wing fences and vortex generators, can have application to problems at both subsonic and transonic speeds. In addition, some of the predictive figures of merit that have been found to be applicable to the subsonic problem (e.g., lift-curve breaks, slope of the lift curve after maximum lift, asymmetric rolling moments, and unstable roll damping) can also be applicable to the transonic wing-drop problem.

The study included an effort to identify specific approaches and relevant data that relate to the wing-drop phenomenon and could be useful to the abrupt-wing-stall (AWS) analysis process. Thus, all aspects of the phenomenon were reviewed in terms of analysis tools—flight data and observations, static and dynamic wind-tunnel tests, and computational analysis. The survey was limited to information available in the open literature. It is known that many other aircraft experienced similar problems during development programs, but the lack of availability of literature excluded them from this review.

Background

The problem area addressed by the AWS Program[1–17] is the unexpected occurrence of highly undesirable, lateral-directional motions at high subsonic and transonic maneuvering conditions. As will be discussed, these motions can have a severe impact on the mission effectiveness of fighter aircraft, particularly under precision air-to-air tracking conditions. In addition, if motions such as wing drop are particularly violent and the roll attitude changes are very large, safety of flight becomes a major concern. Because these degraded characteristics are often unpredicted, they are usually first encountered in flight, where analysis and problem solving are very expensive and difficult.

In contrast to the recent advances made in other critical aerodynamic regimes (e.g., high-angle-of-attack technology), the current situation for stability and control technology for transonic

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*Senior Consultant; jrchambers@cox.net. Member AIAA.
†Senior Research Engineer, Configuration Aerodynamics Branch, MS 499; r.m.hall@larc.nasa.gov. Associate Fellow AIAA.

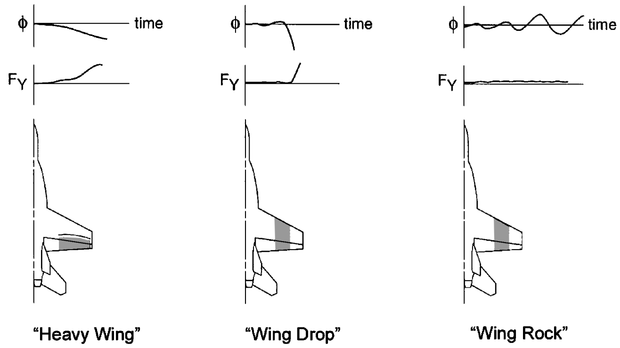


Fig. 1 Terminology associated with uncommanded lateral motions.

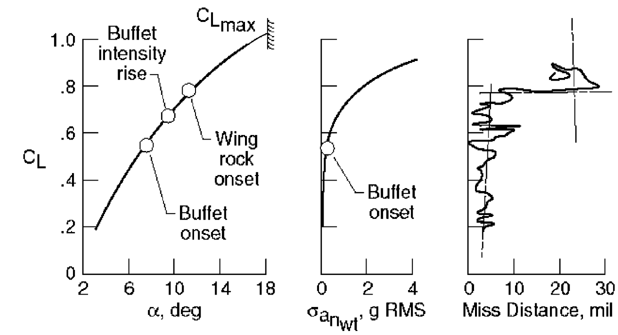


Fig. 2 Typical effects of buffet and wing rock on tracking accuracy.

maneuvering was found to be in a relatively poor state. This situation has resulted from several factors, including the fact that current fighters with high thrust/weight (T/W) ratios now routinely exploit an expanded transonic maneuver envelope, encounter very complex flow separation phenomena at transonic speeds, and are unable to mitigate aerodynamic problems in many cases through use of the flight control system and control augmentation.

Terminology

Several types of uncommanded lateral-directional motions have been encountered at transonic speeds by high-performance aircraft (Fig. 1). In the literature, these motions are frequently referred to as heavy wing, wing drop, and wing rock. The sketches in Fig. 1 depict the time histories of bank angle ϕ and the pilot's lateral stick force F_Y during typical encounters. The shaded areas on the outer wing denote notional areas of flow separation. Heavy wing refers to uncommanded asymmetric roll resulting from asymmetric shock-induced separation over the aft portion of the wing. The flow separation usually reduces aileron effectiveness and reduces lift on the wing panel, resulting in increased aileron deflection and stick force required to maintain trimmed flight. Wing drop refers to abrupt, irregular, and nonperiodic lateral motions. If severe, wing drop can result in sudden, large roll attitude changes of 90 deg or more, with no inherent tendency to return to wings-level flight. In less severe cases, wing drop can be followed by an inherent tendency to return to wings-level conditions independent of pilot actions and can be the precipitator of oscillatory wing rock. Wing drop is characteristically caused by asymmetric wing stall (especially sudden and abrupt leading-edge stall) and at transonic conditions is complicated by unsteady shock-induced separation. Wing rock refers to periodic lateral-directional motions that are dominated by oscillatory rolling motions. Wing rock can be divergent, but in most cases the motions usually grow to a limit-cycle, periodic motion of limited amplitude. The literature cites many references that theorize various causes of wing rock (loss of static stability, hysteresis, nonlinear static moments, and loss of aerodynamic damping in roll). Limit-cycle wing rock is a highly nonlinear phenomenon involving kinematic interchanges of angle of attack and sideslip, which results in alternate stalling and reattachment of flow on the wing panels, nonlinear static and dynamic aerodynamics, and frequency-dependent damping.

The foregoing motions, especially wing drop and wing rock, can be randomly exhibited during a single flight by a specific airplane at transonic conditions. The reader is cautioned that terminology used in the literature is frequently applied in a loose manner (e.g., wing drop used when wing rock is experienced and vice versa), and that examination of the details and nature of the motions encountered is recommended.

Effects of Buffet and Wing Rock on Tracking Accuracy

Much of the historical documentation of the impact of uncommanded lateral-directional motions on mission effectiveness came from studies of buffet and maneuver characteristics of emerging fighters in the early 1970s, when the advent of high T/W fighters and the post-Vietnam emphasis on air superiority were emerging. At that time, the significance of buffet on precision tracking during air-to-air tasks was a major concern during the development of new air superiority and lightweight fighters. This concern resulted in numerous flight tests and wind-tunnel studies to evaluate major factors that influence tracking accuracy and to optimize configurations. The data shown in Fig. 2 were obtained during typical research flight evaluations of gun-tracking performance at the NASA Dryden Flight Research Center.[18]

The plot on Fig. 2a shows the angles of attack for the onset of buffet, the rise in intensity of buffet level, and the onset of wing rock. As indicated, all of these phenomena occurred before maximum lift was reached for the configuration under study. Figure 2b shows the variation of airframe buffet level (accelerations at the wing tip) with lift coefficient. For this particular configuration, the buffet intensity continued to increase beyond onset and could theoretically be used as a cue to the start of wing rock and other undesirable phenomena; however, this characteristic has not been true for many fighters that exhibit a relatively constant level of buffet with increasing lift coefficient, thereby providing little warning of impending conditions at higher angles of attack. Although the effects of buffet on tracking precision during gun-tracking tasks was the primary motivation for conducting the evaluation, the studies provided valuable insight to the impact of uncommanded lateral motions on mission effectiveness. For example, the results shown on the right of the figure illustrate that the relatively large-amplitude motions involved in wing rock severely degraded the tracking accuracy of the pilot much more than the buffet characteristics. In addition to the angular motions, the wing rock was difficult to control in a precise tracking environment.

Although the significance of gun-tracking miss distances of the order indicated in the chart on Fig. 2c must be reconsidered as a figure of merit with today's weapons systems (potentially more tolerant of miss distance), the results show that uncommanded lateral-directional motions have the potential to completely disrupt the precision of a visual tracking task.

Variation of Onset Angle with Mach Number

Figure 3 shows typical variations of the angle of attack for buffet onset and the onset of uncommanded lateral-directional motions for typical fighter configurations with Mach number. The data illustrate that the phenomena begin at relatively low angles of attack (in contrast to low-speed, high-alpha uncommanded motions) and that the onset angles typically become lower at high-subsonic and low-transonic speeds. As a result of this trend, the uncommanded lateral-directional motions can occur at maneuvering angles of attack and have large effects on flying qualities during air-to-air tasks.

Complexity of the Problem

The challenge of avoiding uncommanded lateral-directional motions at transonic conditions is directly related to the complexity of transonic flows, which involve steady and unsteady shock-induced separation phenomena; and the limited ability of wind-tunnels or Computational-fluid-dynamics (CFD) methods to predict such characteristics before flight (Fig. 4). The critical aerodynamic factors include three-dimensional shock/boundary-layer interactions and

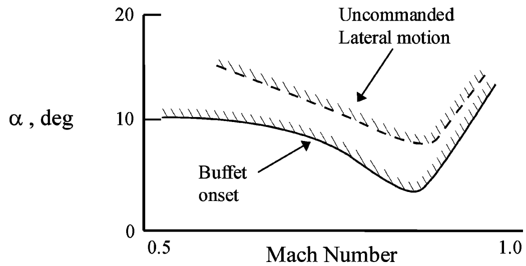


Fig. 3 Typical variation of onset angles with Mach number.

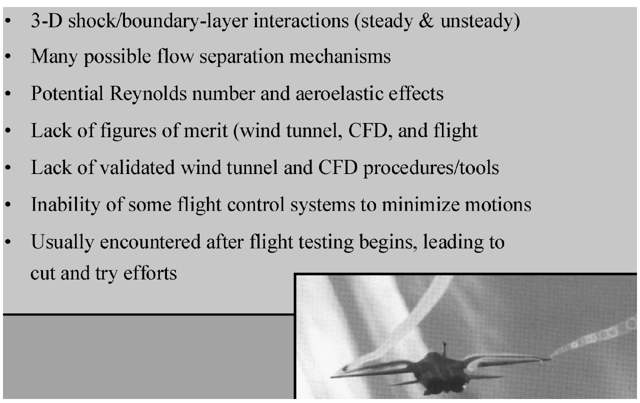


Fig. 4 Factors that contribute to the complexity of uncommanded lateral motions.

numerous flow separation mechanisms, both steady and unsteady. The problem has been aggravated by the lack of availability or validation of wind-tunnel and CFD procedures and tools, and the resolution of major issues such as potential Reynolds-number effects, aeroelastic effects, and modeling requirements for CFD. If the existence of undesirable lateral characteristics can be reliably predicted prior to final design, and if the control system has enough effectiveness and authority to minimize or eliminate the motions, the undesirable aerodynamic phenomena can be mitigated. However, if the aerodynamics overpower the control effectiveness, or the vehicle responds too quickly for the controls to react, the behavior can be unacceptable.

Finally, the complexity of the situation is aggravated when the problems are first encountered in flight tests. The difficulty of analyzing and understanding the fundamental mechanisms involved in the problem, the cost and high visibility of attempting to fix the vehicle in flight during a major weapons system development program, the "cut-and-try" nature of in-flight fixes, and the impact on development schedules all contribute to a very unsatisfactory situation.

Relevant Aerodynamics

The literature[19,20] provides two- and three-dimensional insights into many of the critical aerodynamic phenomena involved in undesirable lateral-directional motions (Fig. 5). The photographs in Fig. 5a show the classical rearward progression of the upper-surface wing shock with increasing Mach number at an angle of attack of 0 deg. Depending on the pressure distribution, aeroelastic effects, and other geometrical characteristics, the movement of the shock system can be rapid and violent, resulting in trim changes and/or loss of lift and control. The sketches in Fig. 5b illustrate the movement of the upper-surface shock with angle of attack at a fixed Mach number. The complex interaction of the pressure distribution, boundary-layer/shock interactions, and other effects can result in a rapid movement of the separation region to the leading edge of the wing and an abrupt loss of lift. The magnitude of lift loss can be extremely large and asymmetric, resulting in a sudden wing drop. The graphic on Fig. 5c depicts the complex interactions that occur between the interacting shocks and the separation regions and the fact that flow separation is a highly three-dimensional problem.

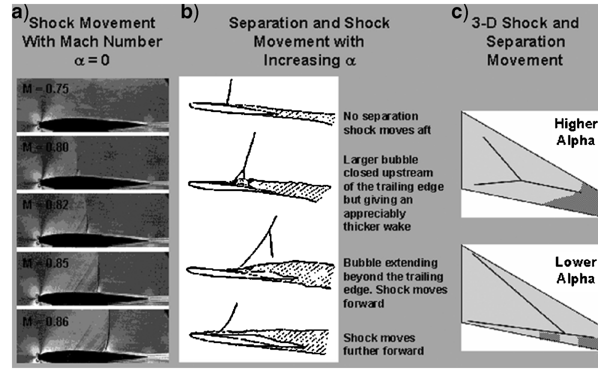


Fig. 5 Illustrations of some of the relevant aerodynamic phenomena that affect lateral motions.

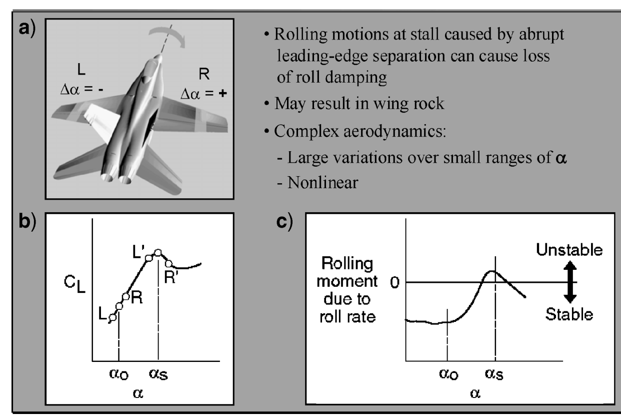


Fig. 6 Relevant dynamic aerodynamic phenomena.

This illustrative characterization of the factors causing wing-drop/rock motions is greatly simplified, inasmuch as other steady and unsteady phenomena are known to exist at these conditions. For example, the chaotic and unstable wing shock oscillations that have been observed in wind-tunnel tests[4] and flight would be expected to have profound effects on the factors that initiate uncommanded lateral motions. Analysis of wind-tunnel data for complete configurations for these conditions has proven to be a formidable task.

Relevant Dynamic Phenomena

In addition to the foregoing steady and unsteady aerodynamic phenomena, wing-drop/rock motions can be caused by aerodynamic factors resulting from the dynamic rigid-body motions of the airplane. Specifically, the magnitude of the wing-drop motions and the tendencies of the aircraft to exhibit wing-rocking motions can be influenced by the trends of aerodynamic damping in roll. Figure 6 illustrates how the severity of local spanwise separation on the wing influences roll damping. Figure 6a shows the effects of a rolling motion to the right on the local flow conditions at individual wing stations on the upgoing (left) and downgoing (right) wing panels. As a result of the rate of roll, the upgoing wing station L sees a decrease in local angle of attack, while the downgoing section R on the right wing sees a local increase in α of the same magnitude. Depending on the local lift-curve slope at each station, the net effects of the rolling motion can augment (propel) rather than damp the motion.

The plot in Fig. 6b can be used to analyze the lift produced at the local sections L and R during a roll to the right. For unstalled angles of attack, such as that for the airplane at the open circular symbol at α_0, the local angles of attack at L and R are decreased and increased by the same increment. The increase in α on the downgoing section R results in an increase in lift at that section, whereas the decrease in α on the upgoing section L results in a loss of lift at that section. The integrated effect of the foregoing is a net rolling moment that opposes (damps) the roll rate.

When the airplane angle of attack increases to that where flow separation occurs on the wing (α_s), the local increase in alpha at section R results in a loss of lift that is larger than the loss of lift on the upgoing section L. Thus, a net rolling moment that augments the roll rate (propelling) is created. This unstable aerodynamic damping in roll can cause wing-rock tendencies and will impact the magnitude of roll rate and motions that occur following wing drop from other causes (for example, large roll asymmetries caused by severe, abrupt stall of one wing panel in a wing-drop event).

Shown in Fig. 6c is the trend of rolling moment caused by roll rate with angle of attack for the case discussed. The abrupt loss of roll damping and band of angle of attack for which the roll damping is unstable is depicted. The discussion has considered small perturbations about the trim flight condition; however, the dynamic motions of wing drop and wing rock typically involve large-amplitude motions and nonlinear effects. Many informative studies[21–26] of subsonic wing-rock aerodynamic mechanisms have been published. These past studies have highlighted the importance of roll damping and other forcing functions such as unsteady lateral moments caused by oscillating shocks.

One important aspect of the potential impact of aerodynamic damping in roll should be noted: In the course of this study, it was determined that very few wind-tunnel or flight-derived measurements of the damping-in-roll characteristics of fighter aircraft configurations have been made or published for transonic maneuvering conditions involving massively separated flows.

Sources of Information and Approach

The approach used in the review was to conduct exhaustive literature reviews and to interview key personnel that were involved in transonic maneuvering research in NASA, U.S. Department of Defense, and industry. Personal discussions and interviews were also held with numerous individuals (active and retired). The material was examined for relevance to the transonic conditions of interest and for documentation of uncommanded lateral motions. Uncommanded motions at other flight conditions, such as low-speed, high-angle-of-attack lateral motions near stall or in the power approach configuration, were intentionally excluded from the review. For more detailed discussions, the reader is referred to the references.

In addition to experiences in specific aircraft development programs, many studies of the fundamental transonic shock-induced separation effects associated with wing-dropping behavior are available in the literature. For example, the NACA conducted research on the phenomenon in the early 1950s using rocket-propelled models[27] and aircraft flight tests.[28]

In the review, it was found that documented flight tests by the NASA Dryden Flight Research Center to evaluate transonic maneuverability and buffet effects and individual industry papers were especially informative. The Dryden flight tests[18] were conducted in the early 1970s to assess the impact of airframe buffeting on tracking capability, but they revealed considerable information on uncommanded lateral motions. Aircraft evaluated included the F-104, F-5, F-8, T-38, F-111, YF-16, YF-17, and F-15.

The current study was directed at three critical products: 1) documentation of uncommanded lateral-directional motions, 2) relevant data (wind-tunnel, flight, etc.) available in the open literature (i.e., nonproprietary), 3) discussions of analysis techniques and tools, and 4) figures of merit.

A list of references that document characteristics of specific airplanes and other reports that provide generic information felt to be especially valuable for analysis of uncommanded lateral-directional motions at transonic speeds is provided at the end of this paper.

Results

The results of the historical survey are very informative and contain substantial "lessons learned." The literature identifies a large number of aircraft programs—over 20—for which substantial uncommanded lateral-directional motions occurred, typically during the early flight test development phase of the programs. Photographs of some of the aircraft are presented in Fig. 7. The impact of the motions had varying degrees of severity such that in some cases

Fig. 7 Aircraft programs that experienced documented uncommanded lateral-directional motions.

the characteristics were mission limiting; in other cases the motions were detected by pilots, but regarded as minor or significantly removed from the operational envelope; and some configurations used flight control technology to mitigate the motions.

One common aspect of the documentation is that the uncommanded motions had not been predicted before flight. In most programs, the development team was alert to anomalies that occurred during wind-tunnel testing, such as violent dynamic motions of sting-mounted models near maximum lift, but analysis of the phenomena involved was limited and uncertain, and tunnel testing was usually curtailed because of model and tunnel operational safety issues. Major issues, such as the potential impact of Reynolds number on asymmetries, and the interpretation of dynamic moment measurements further clouded the issue of predicting flight behavior. As a result of these limitations to tunnel testing, appropriate figures of merit for wind-tunnel tests and analytical studies typically were not identified or validated before the problem was encountered in flight. Thus, the validation of figures of merit was not accomplished for most configurations. Typically, a great deal of cut and try was required during the flight phase, without a clear understanding of the flow physics causing the problem. The specific programs discussed herein should be viewed from a lessons-learned perspective. That is, most of the problems were identified in early flight tests. Ultimately, fixes were adopted for many of the vehicles, including rescheduled leading- and trailing-edge maneuver flaps.

The review identified several excellent examples of analysis of transonic wing-drop/rock phenomena. Unfortunately, in every case the analysis occurred after the undesirable characteristics had been encountered in flight. Foremost among these studies was research conducted by Northrop and NASA Ames Research Center[29,30] for the F-5A, and the Royal Aeronautical Establishment[21] for the Gnat trainer. Each of these studies will be discussed later.

Figures of merit for wind-tunnel testing and some design approaches have been suggested in the literature; however, even the most optimistic researchers involved in the past studies admitted that a great deal of work remained to be accomplished before a valid approach for the prediction and elimination of undesirable transonic lateral-directional motions could be implemented.

Documented Aircraft

The philosophy taken in the review was to only include case studies where documented results are available for the specific airplane. Unfortunately, most high-visibility, time-constrained weapon systems development programs do not document such data once the vehicle enters fleet usage. A substantial part of the information presented herein was obtained from technical reports, which included quantitative information and actual flight time histories. The approach used to present the results consists of a brief, anecdotal review of each airplane, a list of references for more information, and a more detailed discussion of experiences for five specific airplanes.

F-84

One of the earliest experiences of the wing-dropping tendencies of jet aircraft at high subsonic speeds was the Republic F-84 (not shown in Fig. 7). The early straight-wing version of the airplane exhibited strong heavy-wing tendencies and abrupt roll-offs between Mach numbers of 0.8 and 0.9. NACA flight investigations of the aircraft at the NASA Ames Research Center[31,32] concluded that the behavior was attributable to loss of aileron effectiveness and strong dihedral effect, which combined to make lateral control very sensitive for small angles of sideslip.

F-86

The F-86A was subject to shock-induced separation at transonic speeds, which resulted in wing-dropping behavior. Extensive studies of vortex generators, locked slats, boundary-layer fences, and wing-tip slat extensions were conducted at NASA Ames Research Center[32,33] to fix the problem. The solution adopted consisted of vortex generators which increased the aileron effectiveness and reduced the asymmetry of flow separation during sideslip.

G-91

The Fiat G-91 used by the Italian Air Force also encountered wing-drop tendencies within a Mach-number range at the upper end of the subsonic flight regime. The fix consisted of vortex generators, which also improved maximum lift.[34]

A-4

The X-model of the A-4 series could easily enter the transonic region with a 10-degree dive. Although buffet was light and only a small pitch-trim change occurred, an abrupt wing drop to either the left or right with roll angle excursions of over 30 degrees was a major problem.[35] Over 11 different vortex generator patterns were tried before arriving at a fix, which consisted of a pattern with one row on the slat and one row in front of the aileron.

T-45

Preproduction versions of the T-45 trainer exhibited severe wing drop in flight evaluations at moderate and low speeds. The low-speed wing-drop problem was mitigated by the addition of leading-edge slats. The airplane also exhibited heavy-wing characteristics at high subsonic/transonic conditions because of shock-induced separation, which produced a substantial reduction in aileron effectiveness. Vortex generators were used to delay the heavy-wing problems to beyond the operational envelope.[36]

F-104

The F-104 was used in the initial series of early NASA Dryden Flight Research Center studies of the impact of leading- and trailing-edge flap deflections on transonic buffet and maneuvering performance. These investigations, initiated in the late 1960s, were among the earliest definitive studies of the impact of aircraft flight parameters on transonic handling qualities during air-to-air tracking tasks. Leading- and trailing-edge flaps were deflected independently and in various combinations from 0 to 10 deg. A wing-rock problem was experienced with the F-104 at an angle of attack of about 12 deg over the entire speed range and was especially severe for larger flap deflections.[37]

F-8

In addition to the F-104, Dryden flight-test evaluations of the effects of leading-edge and trailing-edge flap deflections on buffet included the F-8A and F-8C. Nine different combinations of leading- and trailing-edge flap deflections were flown.[38] Wing rock was experienced over the entire range of Mach numbers tested. At subsonic conditions, the leading-edge flap was more effective in delaying the onset of wing rock; however, at the transonic speeds the leading- and trailing-edge flaps appeared to be equally effective.

EA-6B

The EA-6B exhibits minor, but noticeable, uncommanded wing drop during maneuvers at transonic conditions ($M > 0.75$). This characteristic is most noticeable when pods or tanks are installed. Flight tests showed that the roll excursions are easily correctable with control inputs. An extensive Navy/NASA/Grumman study to develop an advanced capability for the EA-6B included major improvements in aerodynamic performance, stability, and control.[39]

F-4

Navy and Air Force versions of the F-4 exhibited wing rock over most of the subsonic flight regime[40–42] up to Mach numbers of about 0.8. The characteristic was caused by loss of aerodynamic damping in roll and was delayed and minimized by the addition of leading-edge slats to the airplane in later versions.

F-5

The entire series of the F-5 family (F-5A, F-5E, F-5F, and the more advanced F-20) and the T-38 exhibited wing rock/drop phenomena across the speed range.[29,30,43,44] Outstanding wind-tunnel and flight studies of the causal factors have been published by Northrop. Of all past investigations studied in the current analysis, this work provides the most informative data for static and dynamic aerodynamic phenomena associated with transonic wing rock.

F-111

A flight research program was undertaken at Dryden[45] to demonstrate the improvements in transonic maneuverability that resulted when the F-111A airplane was equipped with a supercritical wing. The supercritical wing airplane was known as the F-111 TACT (Transonic Aircraft Technology) airplane. Wing sweep positions of 26, 35, and 58 deg were flown, and the performance and precision controllability of the basic and modified airplanes were documented. The supercritical wing significantly improved the buffet-free envelope of the airplane. Wing rock was encountered for both airplanes for low wing sweep angles during maneuvers at high subsonic speeds, with the F-111 TACT aircraft having the higher onset boundary.

Harrier

The development of the current versions of the British Harrier was preceded by numerous experiences with uncommanded wing drop/rock on earlier versions of the aircraft, beginning with the Kestrel, which exhibited wing rock of over ±25 deg at Mach numbers from 0.7 to 0.9. These motions were so severe that pilots intentionally restricted maneuvers to lower angles of attack. The subsequent AV-8 and Harrier Mk GR1 configurations underwent considerable modifications with wing vortex generators, wing leading-edge fences, wing-body strakes, wing leading-edge airfoil modifications, etc. before arriving at acceptable lateral flying qualities. Considerable disagreement between predictions based on tunnel results and flight experiences were encountered.[46] Excellent discussions of the details of these development programs with regards to wing drop/rock and the development of the wing configuration for the Harrier are also available. Of particular interest are data of lift and rolling-moment variations for the basic Harrier and the beneficial effects of a wing-body strake modification on lateral characteristics near wing stall conditions at high subsonic Mach numbers.[46,47]

Additional information on aerodynamic data for the AV-8B at high subsonic speeds is available,[48] including flight-derived measurements of unstable trends of aerodynamic damping in roll with angle of attack at high subsonic speeds.

Gnat

The British Folland Gnat was the subject of extensive studies of wing drop and wing rock after these undesirable characteristics had been encountered in flight tests. The emphasis in the studies[21,42,49] was from a flight dynamics perspective, so although the critical aerodynamic parameters are identified and figures of merit proposed no analysis of detailed wing aerodynamics, such as pressures, was documented. The studies are particularly informative relative to documentation of unstable trends of damping in roll during maneuvering conditions at high subsonic speeds.

F-15

Documentation of wing-rock tendencies for the F-15 was found in two references. A preproduction version of the F-15 (prior to final design of the flight control system) was evaluated at NASA Dryden in the 1970s (Ref. 50). Mild-to-moderate wing rock was encountered at angles of attack above about 10 deg over the Mach range tested. Maximum roll rate in wing rock was about ±20 deg/s. The second reference is a Master's thesis[51] written in fulfillment of an advanced degree at the Air Force Institute of Technology in the 1990s. This thesis also included actual flight tests of an F-15D (and other aircraft) and analytical predictions of the motions. The discussion includes a characterization of the rolling motions of wing rock for the F-15D and compares them to those of other aircraft.

YF-17

During transonic buffet evaluations at NASA Dryden,[52] the YF-17 exhibited wing-rock and wing-drop motions that doubled the tracking error. The characteristics of the aircraft were of particular interest to the AWS Program, in view of the role of the YF-17 as a predecessor to the F/A-18 series.

YF-16

The YF-16 was also evaluated during the Dryden studies[18] with scheduled leading-edge flaps and with zero leading-edge flap deflection. Fixed deflections of both leading- and trailing-edge flaps were also evaluated. With zero leading-edge flap deflection, the aircraft exhibited uncommanded wing-rock and abrupt wing-dropping motions. Pilot comments refer to mild wing rock at transonic conditions, and the flight report states that the highly effective lateral control augmentation suppressed the wing rock.

Aircraft Summary

The preceding discussion reveals that uncommanded lateral-directional motions at transonic speeds have been a common experience for many high-performance aircraft and that such characteristics should be investigated in the early design stages for future aircraft. With regard to the AWS Program, the results clearly illustrate that the wing drop exhibited by the preproduction versions of the F/A-18E/F is not, by any means, a unique situation. The scope of airplane wing configurations covered by the discussion herein included wing sweep angles from 0 to 45 deg, aspect ratios from 2.5 to 7.6, and a range of leading- and trailing-edge flap designs, including no flaps.

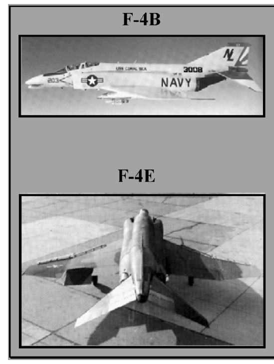
Highlights of Specific Experiences

Certain aircraft documented in this study deserve special discussion because of special phenomena or analysis approaches that were judged to be of particular interest to the AWS effort.

F-4 Experiences

The uncommanded lateral motions of the F-4 are highlighted because they involve highly nonlinear dynamic effects, which should be considered in analyses of transonic wing drop/rock. Nonslatted versions of the F-4 exhibited wing-rocking motions at high angles of attack across the range of subsonic speeds (Fig. 8). Extensive documentation of this tendency with time histories is available in Air Force Test Center, AGARD, and NASA reports.[40] Although it completely disrupted gun-tracking solutions, the onset of wing rock on the F-4 was used by pilots as a natural warning of an even more severe deficiency—an impending nose slice tendency at higher angles of attack that normally led to loss of control and spin entry.

In NASA research, the cause of wing rock on the F-4 was determined to be loss of aerodynamic damping in roll near stall. Extensive forced-oscillation wind-tunnel tests with an F-4 model showed the damping to be slightly unstable at stall and very nonlinear such



Early models (no le devices):
- Large-amplitude (±30°), limit-cycle wing rock
- Used as a cue for impending nose-slice departure
- Control system ineffective in damping motions

Causal Factor/Figures of Merit:
- Leading-edge stall
- Lift-curve break, randomness in rolling moments at stall, loss of damping in roll

Resolution:
- Leading-edge maneuver slats

Fig. 8 Comments regarding F-4 airplane experiences.

that at relatively small amplitudes of roll oscillations (<5 deg) the damping was unstable, but at large amplitudes (>10 deg) the damping became stable.[42] In addition, the frequency of the motion had a large effect, with higher frequencies causing the damping to become stable. When analyzed in a mathematical simulation, the wing rock of the F-4 could only be replicated[53] with these critical nonlinear aerodynamics involved. In addition, free-flying model tests at low speeds duplicated the wing rock of the full-scale airplane.

Another research effort by NASA Langley Research Center involved the use of a free-to-roll balance apparatus for an evaluation of the F-4 wing-rock tendency. Researchers observed that the wing-rock motions seen during the free-flight model tests were typically pure rolling motions, as might be expected because aircraft that are inertially "slender" will tend to move about the axis of least resistance—in this case, the roll axis. It was reasoned that the mechanisms of the wing rock might be captured by a simple test method that permitted only rolling motions. In unpublished low-speed tests, the F-4 free-flight model was sting mounted through the rear on a dummy balance, using a bearing to provide a single degree of freedom in roll. The results of the tests showed excellent agreement with the free-flight test results in terms of angle of attack for onset, and also for the amplitude and frequency of motion. This result, combined with similar Northrop and NASA results for the F-5[29] and others,[54,55] indicated that transonic free-to-roll tests[10] should be examined as a relatively inexpensive test technique for screening configurations early in the design stages for tendencies for uncommanded lateral motions. It might be possible to utilize the same model and tunnel test apparatus for both static and free-to-roll testing and thereby conduct conventional static tests and free-to-roll tests in a relatively rapid sequence during a specific tunnel entry. In this regard, the free-to-roll technique offers considerable advantage over other approaches, such as forced-oscillation and rotary-balance tests where special models and tunnel entries are required. Of course, after configurations have been screened the latter tests might still be required to obtain quantitative data on roll damping for simulation and more refined analysis.

Analysis of the F-4 wing-rock phenomena provides insight to the kinematic interchanges of angle of attack and sideslip that occur in such motions, interacting with the local wing sectional-lift characteristics to impact lateral motions as discussed earlier. Figure 9 depicts the motions exhibited during the first phase of wing rock involving initial motions to the right. The airplane depicted in Fig. 9a is flying at zero sideslip and zero bank angle at some initial angle of attack. An acceleration in roll occurs (caused by an abrupt rolling-moment asymmetry or other disturbance), resulting in a rolling motion to the right.

As the airplane rolls to the right about the body axis, the kinematics of the motion results in a reduction in airplane angle of attack and the generation of sideslip. Figure 9b shows the airplane at the maximum right-wing-down attitude during the wing-rock cycle, at which time the roll rate is zero and the dihedral effect acts through the sideslip to create a restoring spring force to drive the airplane back to a wings-level condition. The restoring roll acceleration is a maximum at this point, and the airplane rolls back towards the wings-level condition. However, if the aerodynamic damping in roll

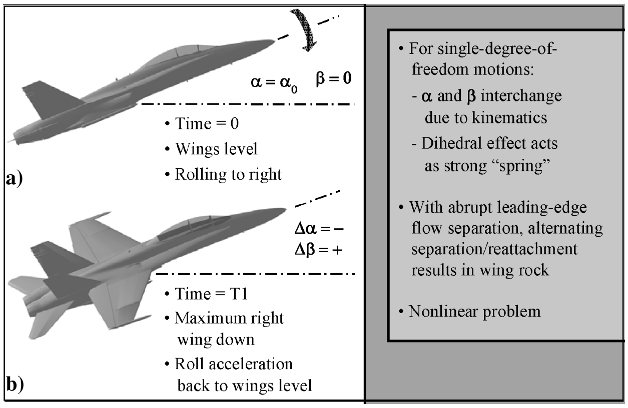


Fig. 9 Kinematic relationships during wing-rock motions.

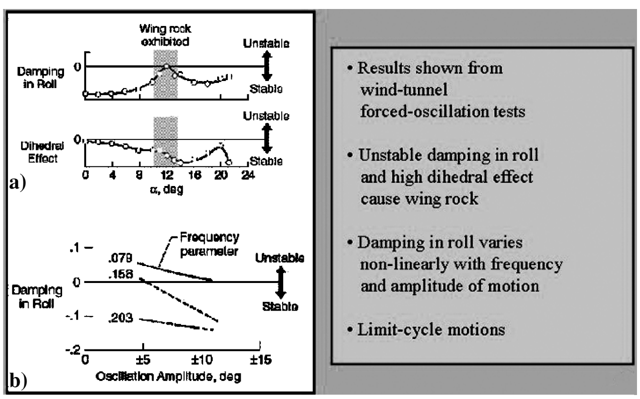


Fig. 10 Wind-tunnel data illustrating trends of aerodynamic damping in roll for F-4 model.

(rolling moment caused by roll rate) is unstable a residual roll acceleration to the left is present at the wings level-condition, and the cycle repeats to the left.

Flow on the wing can be observed to reattach and separate during these motions, and the reattachment phenomena is especially visible during free-to-roll tests. Mathematical modeling of the wing rock is obviously a very nonlinear problem, and simulation of the motions for pilot evaluations should consider the modeling requirements for large-amplitude motions.

Presented in Fig. 10 are F-4 wind-tunnel data obtained at low speeds during forced-oscillation tests.[56] As shown by Fig. 10a, the marked degradation of damping in roll at wing stall near $\alpha = 12$ deg is accompanied by strong, stable trends in dihedral effect. This combination interacts as described in the preceding chart to promote the wing-rock tendency. (Note the severe "nose slice" of the F-4 occurs at a higher angle of attack near $\alpha = 20$ deg, where an abrupt loss of dihedral effect combines with a severe loss of static directional stability).

Figure 10b shows measured data with the same model, indicative of the effects of the oscillation amplitude and frequency during the tunnel tests. At low reduced frequencies (0.078), the roll damping is unstable, promoting the wing-rock motion through diverging motions. However, as the frequency increases, or the amplitude of motion increases, the flow separation and reattachment mechanisms result in stable damping. Fundamentally, this trend results in a limit-cycle motion that builds up to a certain frequency and amplitude, then remains constant exclusive of pilot inputs.

Although not based on transonic measurements, the foregoing F-4 data and discussion are presented for background and as an aid to the reader when reviewing the results of the AWS Program[10] for transonic wing-drop/rock aerodynamic phenomena.

Slatted versions of the F-4 also displayed wing rock, but for much lower amplitudes and at significantly higher angles of attack. The effectiveness of the slats in delaying wing stall and the attendant wing

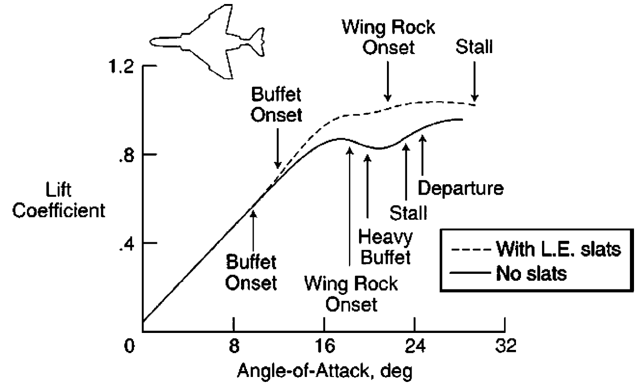


Fig. 11 Lift-curve variations for basic F-4 and F-4 with slats.

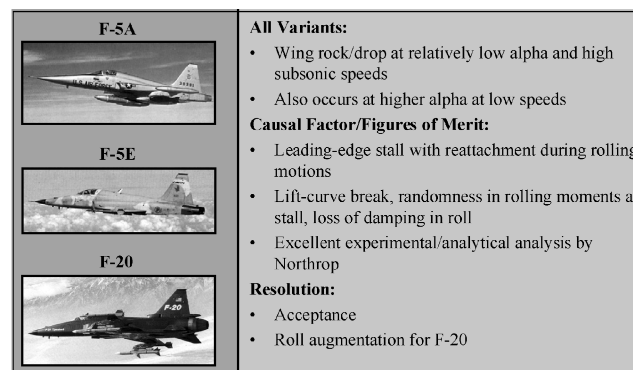


Fig. 12 Comments regarding airplane experiences of the F-5 family.

rock and nose slice is well documented.[21,41] Presented in Fig. 11 are lift-curve variations for the baseline F-4 and for the airplane modified with leading-edge slats. The data reflect the changes created in lift-curve slope by the leading-edge slats. Particularly noticeable is the extension of linear slope below maximum lift (elimination of separation) for the slatted configuration and the delay in onset of wing rock. These trends are suggestive of figures of merit, which were subsequently studied in the AWS Program.[8]

F-5 Experiences

The F-5A, F-5E, T-38 trainer, and the advanced F-20 all encountered unexpected wing rock/drop at certain transonic flight conditions in their respective development programs (Fig. 12). In the case of the F-20, the roll augmentation system was capable of eliminating the motions, once they had been discovered in flight.

This aircraft family also exhibits wing-rock motions at low speeds and higher angles of attack. Although not directly the subject of interest in the AWS programs, some of the flow mechanisms, data, and figures of merit from such tests should be studied for potential relationship to the figures of merit at transonic speeds.

Northrop conducted extensive studies[29,30,43] of the aerodynamics and flight dynamics causing the motions of the F-5A. The results are well-documented, consisting of in-flight and wind-tunnel static and dynamic pressure measurements; dynamic (free-to-roll) wind-tunnel tests; and analytical simulation of the wing-rock mechanism. This particular series of studies was excellent and exhaustive, and it should serve as a model for future analysis approaches.

In a unique experiment[29] in the Ames 11-ft tunnel, Northrop conducted static and semi-free-to-roll tests of an F-5A model to analyze the cause and mechanisms of the wing-rock motions encountered in flight (Fig. 13). Utilizing a 1/7-scale buffet model and a special sting with torsional spring and variable damper, Northrop was able to create, observe, and analyze wing-rock motions exhibited by the full-scale airplane at transonic speeds.

Extensive analysis of buffet, static and unsteady pressures, and model dynamics were documented. Separation and reattachment of the flow was observed and measured by the pressures, and

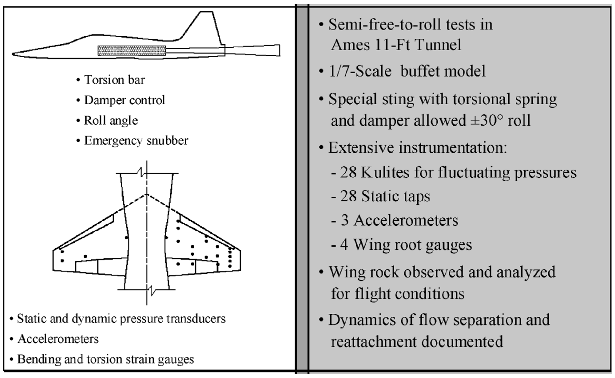


Fig. 13 Overview of elements of the F-5A transonic wing rock wind-tunnel tests.

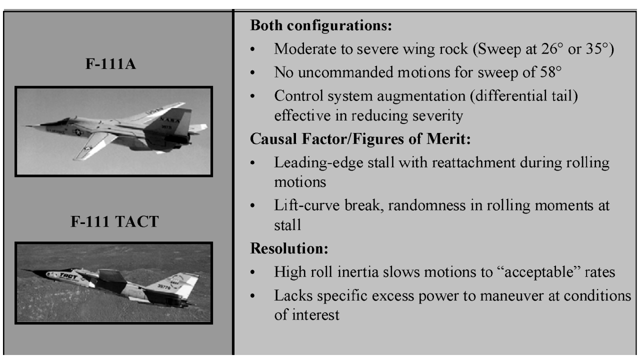


Fig. 14 Comments regarding F-111 airplane experiences.

mathematical modeling of the motions was accomplished. Of particular interest were observations of unsteady shock movements ranging from 20 to 40% of the local wing chord near wing-rock angles of attack. Also, different types of uncommanded motions were measured at transonic conditions. In some cases, the model would exhibit limit-cycle, periodic wing rock with a sustained character. For other combinations of alpha and beta, the model displayed bursts of periodic roll activity following a wing drop event, the motions then damping to near-zero bank angles, then building back up to large bank angles again.

The different uncommanded roll responses possible at transonic conditions as exhibited by the F-5 model, together with the recognition that either the unsteady movement of shock-induced separation on the wing or loss of roll damping could cause wing rock, resulted in a perspective on critical transonic wing-rock mechanisms. In particular, it was hypothesized[57,58] that wing rock could result from either a change from positive to negative aerodynamic damping in roll or from random, aerodynamically forced fluctuating moments caused by unsteady shock movements. Similar variations in model free-to-roll response characteristics[10] were subsequently noted in the AWS Program.

The approach and results of the F-5 study are extremely impressive and served as an inspiration to elements of the AWS Program. The challenge to develop a testing capability that utilizes a common model and test apparatus to evaluate performance and dynamic free-to-roll characteristics ultimately became a major deliverable from the AWS Program.

F-111 Experiences

The characteristics of the F-111A and the NASA F-111 TACT airplane with a supercritical wing were evaluated in the transonic buffet/tracking studies[45] conducted by NASA Dryden in the 1970s (Fig. 14). Wing rock was encountered for both the basic F-111A and the F-111 TACT for wing sweep angles of 26 and 35 deg at high subsonic and transonic speeds. During the development of the supercritical wing and its "flat" pressure distribution, considerable concern had arisen over the potential abruptness of stall progression,

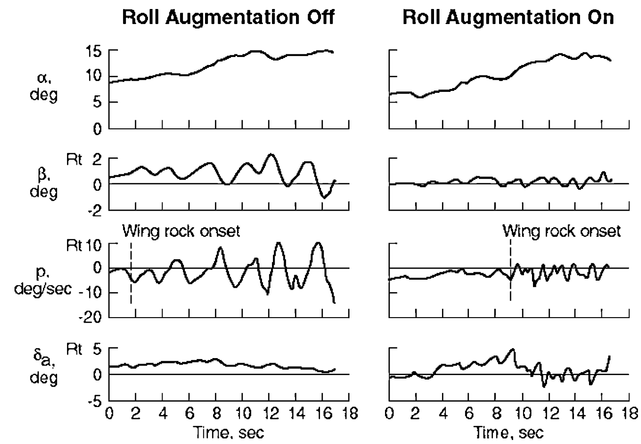


Fig. 15 Effect of roll augmentation system of F-111 TACT airplane.

especially at transonic conditions. Much testing to improve these characteristics for the F-111 TACT design was conducted in the Ames 11-ft tunnel prior to flight. Despite the precursor tunnel tests, uncommanded motions were experienced in flight.

Wing rock was encountered with every high-performance airplane evaluated by Dryden,[18] including the F-111 research aircraft, but the F-111A and F-111 TACT were less affected by wing rock than the other airplanes. This result was attributed to the relatively large roll inertia of the F-111 (more time for pilot corrective actions), the fact that all-moving tails were used for roll control (rather than ailerons or spoilers that aggravate wing rock), and the use of a high-gain stability augmentation system. The relatively poor transonic turning performance of the F-111 with the wings swept forward resulted in large losses in specific excess power P_S and rapid losses in altitude for the wing-drop conditions. Thus, the phenomenon was regarded as occurring significantly outside the usable envelope.

Roll damping measurements for the F-111 configuration were made at subsonic and transonic speeds for continuous rolling motions in wind-tunnel tests at the NASA Langley Research Center.[59] The results revealed a dramatic reduction in roll damping for low-sweep configurations at transonic, maneuver conditions. The data also showed no loss of damping for high wing sweep angles, in agreement with flight experiences.

The F-111's roll augmentation system had a large beneficial effect on the magnitude of the wing-rock motions (Fig. 15). The figure shows the marked reduction in roll rates with the damper operative. The fact that the F-111 used differential horizontal tail deflections for roll control at these conditions is an important factor. The tails operated in a relatively good flowfield, whereas wing-mounted controls would probably have been susceptible to the flow separation phenomena on the wing and not been as powerful for roll control. In fact, during the assessment it was found that active use of the wing-mounted spoilers for roll control triggered wing rock at lower onset angles of attack.

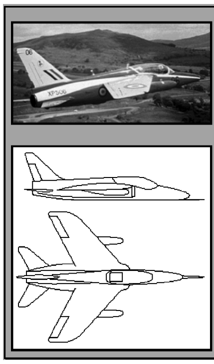
No wing rock was encountered for either of the F-111 airplanes at the aft wing sweep of 58 deg. This result is extremely significant in that basic research and some specific airplane programs (F-16XL, F-106) have indicated that wing-drop/rock has not been experienced for the vortex-dominated flowfields of aircraft with wing sweep angles from about 60 to 70 deg. For sweep angles greater than about 70 deg (when vortical flow phenomena dominate), wing rock has been common.

F-14 Experiences

Transonic wing drop and wing rock have not been exhibited by the F-14, and as a result it is not shown in the matrix of airplanes of Fig. 7. However, two key observations of the lateral behavior of the aircraft are worthy of inclusion for the current survey.

In the early development cycle of the F-14, flight tests revealed the presence of highly undesirable lateral motions at high-angle-of-attack conditions. With wing full-span leading-edge maneuver slats

Fig. 16 F-14 does not exhibit wing-rock tendencies at transonic conditions.



Characteristics:
- Severe wing rock and less frequent wing drops at high subsonic/transonic speeds
- No wing rock for airplane with tanks on
- No roll augmentation system

Causal Factor/Figures of Merit:
- Lift-curve break, randomness in rolling moments at stall
- Loss of aerodynamic damping in roll (no aero flow physics available)
- Excellent study by RAE with wind-tunnel dynamic measurements and flight PID

Resolution:
- Acceptance

Fig. 17 Comments regarding uncommanded lateral motions for the British Folland Gnat airplane.

extended and the wing at relatively low sweep angles (20 deg), the F-14 exhibited wing-rock motions at all subsonic speeds less than about Mach = 0.8 for angles of attack greater than about 15 deg. This wing-rock tendency degraded tracking and had an impact on the development of an automatic spin prevention control concept for high-angle-of-attack conditions.[60] When the automatic controls provided rudder inputs to increase spin resistance during maneuvers, the inputs triggered the wing-rock motions, degrading the effectiveness of the tracking. A subsequent joint NASA/Grumman/Navy research program refined the control system and eliminated the wing-rock problem. Further development of the system by the Navy (Fig. 16) was included in the current digital flight control system now used in fleet aircraft. The lesson learned in the F-14 experience is that the prediction of uncommanded motions such as wing rock can be critical to the design and implementation of flight control system components that are directed at other objectives.

The second F-14 characteristic of importance to the AWS Program is that uncommanded wing rock or wing drop is not exhibited by the airplane for Mach numbers greater than $M = 0.8$. This resistance to lateral motions is attributable to the beneficial aerodynamic impact of increased wing sweep. The automatic wing-sweep scheduler for the F-14 increases the sweep angle as a function of Mach number rapidly from 22 deg at $M = 0.7$ to 68 deg at $M = 0.9$ (Ref. 61). The change in character of the attendant flow separation physics during maneuvers to vortex-dominated phenomena at the higher sweeps is believed to be the major contributor to the mitigation of wing rock/drop. The lack of uncommanded lateral motions at transonic conditions for the F-14 is similar to the behavior of the F-111 for high sweeps, as discussed earlier.

Gnat Experiences

The British Folland Gnat trainer aircraft demonstrated severe wing rock at high subsonic speeds (Fig. 17). Use of parameter identification methods using flight-test data identified an abrupt loss of roll damping as the mechanism causing the wing rock.[21] Interestingly, the addition of relatively large wing external tanks alleviated the wing-rock motions, although causing unsatisfactory longitudinal motions. The alleviation of wing rock by the tanks was reflected in increased damping in roll characteristics for the configuration. The study included forced-oscillation wind-tunnel tests,[49] and the results of the oscillation tests verified the severe loss of roll damping at angles associated with the onset of wing rock.

An important observation regarding the wind-tunnel forced oscillation tests of the Gnat was that when the angle of attack of the model was increased to the value associated with the abrupt loss of damping in roll the model oscillated too violently in the tunnel for safe operations and the tests had to be stopped. This result suggests that a free-to-roll type test would have been extremely informative and could have predicted the wing-rock tendency. Together with the results already discussed for the F-4 and F-5A, the experiences with the Gnat point to free-to-roll testing as a potentially critical test method.

Interestingly, the Gnat (clean or with tanks) occasionally displayed wing drop of severe character without subsequent recovery by wing rocking. This nonperiodic rolling motion was attributed to the magnitude of the rolling moment induced by asymmetric stall of the wing panels.

The references do an excellent job of defining the need for dynamic aerodynamic data in wing-rock analyses and the importance of parameter identification in the process. Although lacking in fundamental information (e.g., pressures) on aerodynamics, the Gnat experience is one of the most important references for any study related to uncommanded lateral motions, and the techniques and analysis are outstanding. The time histories of Fig. 18 present results of Gnat flight tests at $M = 0.78$, which demonstrate the abrupt change in character of lateral-directional responses at high subsonic and transonic conditions.

The time history on the left shows the airplane's response following aileron and rudder inputs at an angle of attack of about 8 deg to excite the Dutch roll and roll subsidence modes of motion for parameter identification (PID) work. As can be seen, the modes were appropriately excited by the control inputs, and the motions subsequently damped out.

When the angle of attack was increased to about 10 deg, however, an abrupt wing drop occurred, followed by a rapidly diverging wing-rock motion. Subsequent analysis of these motions led to extraction of data from flight tests, and accompanying static and dynamic force tests identified the aerodynamic damping in roll as a major contributor to the uncommanded motions of the Gnat. Presented in Fig. 19 are the variations of aerodynamic damping-in-roll derivative (based on small-amplitude disturbances from trimmed flight) for the Gnat in the basic configuration and with wing tanks at high subsonic speeds. Figure 19a shows the comparison of flight data derived from PID work and wind-tunnel data obtained in small-amplitude

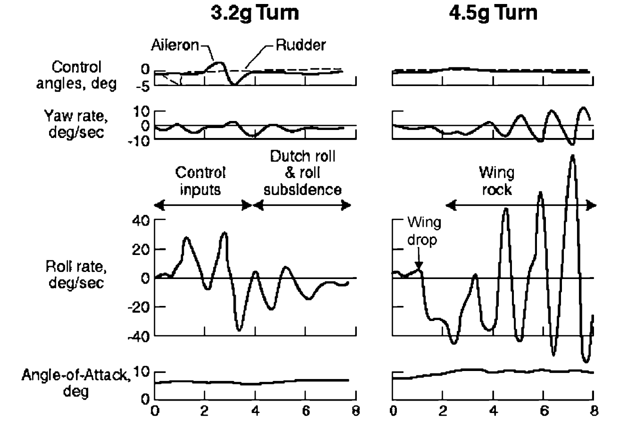


Fig. 18 Responses of the Gnat airplane to pilot inputs at Mach = 0.78.

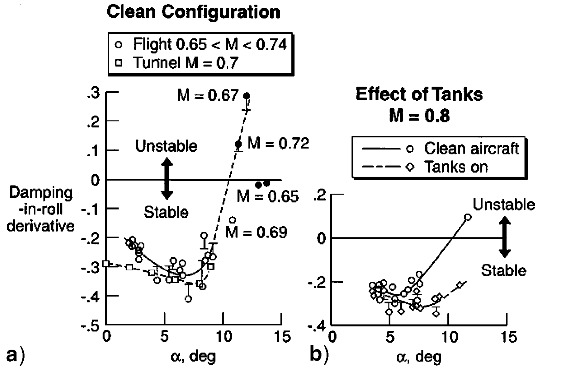


Fig. 19 Wind-tunnel and flight-derived variations of aerodynamic damping in roll for the Gnat.

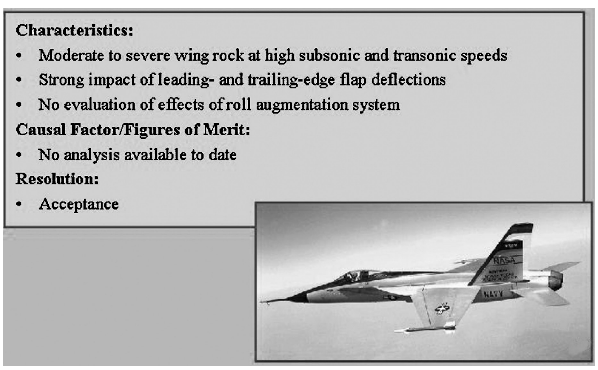


Fig. 20 Comments regarding uncommanded lateral motions experienced with the YF-17 airplane.

forced-oscillation tests. The flight data show an abrupt loss of roll damping near an angle of attack of 10 deg and unstable values at higher alphas. This trend correlates well with the divergent motions observed in flight. The wind-tunnel data correlate well with flight up to 10 deg, but major model fluctuations on the sting curtailed the testing from a safety concern. Apparently, the model was reacting to the same loss of damping experienced by the airplane at about the same angles of attack.

In Fig. 19b, data taken from flight PID show that the large, wing-mounted tanks on the Gnat caused a marked improvement in roll damping. The aerodynamic reason for this improvement is not analyzed in the references, but might be related to less abrupt flow separation characteristics on the wing.

YF-17 Experiences

Another informative flight investigation involving uncommanded transonic lateral motions is the Dryden evaluation[52] of the YF-17 during the Lightweight Fighter competition (Fig. 20). At the time of the evaluation, both the YF-16 and YF-17 were being developed with emphasis on transonic maneuvering, and the application of leading- and trailing-edge flaps to buffet alleviation was being assessed and matured. In addition, the flight control systems of both airplanes were under development.

In the Dryden flights, the YF-17 was evaluated with and without scheduled leading-edge flaps, and the automatic flap maneuver schedule had not been optimized. Pilots reported that the YF-17 tracked targets as well at normal accelerations of 8 *g* as earlier fighters did at 4 *g*. They considered the aircraft to be one of the best tracking airplanes they had flown. Wing rock, in varying degrees of severity, was present for all YF-17 configurations under maneuvering conditions. In some instances, pilot inputs aggravated the wing-rock motions. The angle of attack for wing-rock onset reduced dramatically when Mach number was increased from 0.6 to 0.8 (16 to 8 deg, respectively). Roll rates during the wing rock were on the order of 20 deg per second. Three different time histories of relatively severe wing rock during tracking maneuvers are

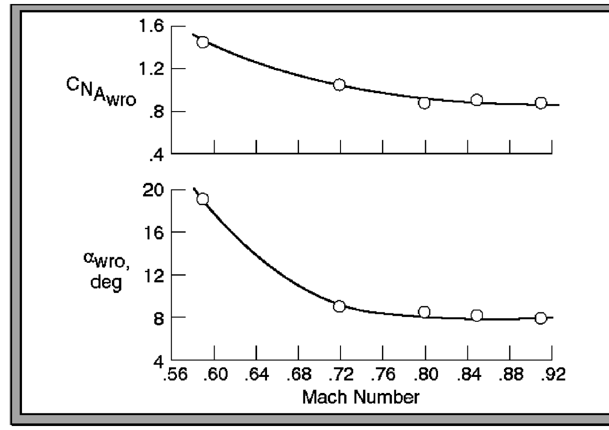


Fig. 21 Variation of onset conditions for wing rock exhibited by the YF-17 airplane.

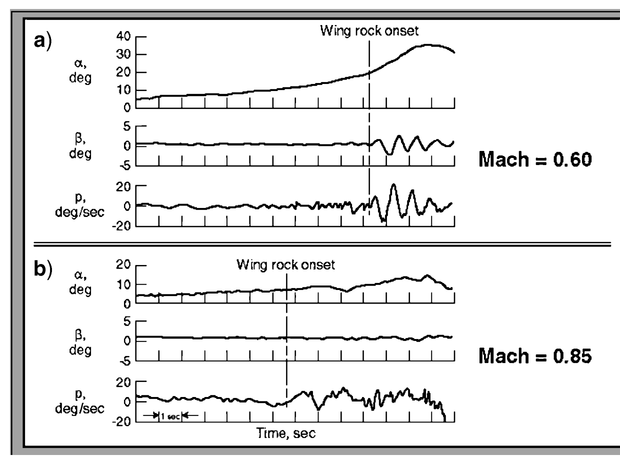


Fig. 22 Illustrations of wing rock motions for the YF-17.

given in the references. The references also provide summaries of the wing-rock onset boundaries for the YF-17 as a function of Mach number. An interesting observation was that increased deflection of the trailing-edge flap was more effective than leading-edge deflections at a Mach Number of 0.8.

Unpublished references state that the YF-17 wing-rock tendencies were related to aeroelastic effects and that shock-induced effects interacted with the structural modes and flight control system to aggravate the wing rock. Documentation and validation of this hypothesis have not been possible.

The trends with Mach number of normal force at wing-rock onset and the angle of attack for onset are presented in Fig. 21. Note the sharp decrease in angle of attack as Mach number increased from about 0.6 to 0.7.

Time histories of the wing-rock motions encountered in flight tests of the YF-17 are shown in Fig. 22. Figure 22a shows the character of wing rock experienced during flight at a Mach number of 0.6, with abrupt onset of periodic wing rocking motions. For a Mach number of 0.85, the wing rock consisted of relatively random motions and excursions in roll rate.

Lessons Learned

This review of experiences from past airplane development programs has identified several important lessons that should be considered in approaches to best practices for the prevention of uncommanded lateral motions for transonic maneuvering aircraft. These lessons have emphasized the complex nature of transonic flow separation phenomena, the difficulty in reliably predicting steady and unsteady aerodynamic characteristics, and which geometric characteristics promote or eliminate wing drop/rock:

1) The interpretation of conventional static wind-tunnel data for predictions of wing drop/rock has been an art, with many conflicting experiences.

2) Confidence in static figures of merit for the prediction of wing drop has been very low, characterized by observations such as, "It does not seem possible to find convincing correlation between tunnel measurements and flight behavior, although Cl at zero sideslip may give some qualitative indication of wing drop tendencies."[19]

3) Abrupt leading-edge stall has been the most common aerodynamic cause of uncommanded lateral motions (wing drop and wing rock) at transonic speeds.

4) Wing leading-edge flap/chord ratios and flap deflections are extremely important factors in preventing leading-edge stall.

5) Marked reductions in aerodynamic damping in roll are usually associated with wing rock/drop. The reduced damping can also become unstable and vary in nonlinear fashion with roll rate, frequency of oscillatory motions, and angle of attack and sideslip.

6) Unsteady shock oscillations and shock-induced separation areas occur in an unsymmetrical fashion between each wing panel, providing a random, chaotic forcing function for the onset of wing drop or wing rock at transonic maneuvering conditions.

7) Uncommanded lateral motions observed at transonic conditions can be of markedly different natures, including aperiodic heavy wing behavior caused by asymmetric trailing-edge separation, aperiodic abrupt wing drop caused by asymmetric wing stall, periodic limit-cycle wing rock caused by loss of roll damping, and time-dependent, semiperiodic bursts of periodic motion caused by chaotic, unsteady shock movements.

8) Control system roll-rate augmentation has been very beneficial in mitigating the undesirable motions for those configurations with effective controls.

9) Wing rock and wing drop have not been a significant problem for airplanes with wing sweep angles between about 60 to 70 deg.

Recommendations for Research

Based on this review of past airplane programs and the general literature for uncommanded lateral motions at transonic maneuvering conditions, several recommendations for research thrusts are suggested. References are noted in instances where the AWS Program has already responded to the recommendations.

1) Develop a "cookbook" of best design practices for approaches to vehicle design that avoid uncommanded lateral motions. Provide definitions of the appropriate approaches for geometrical layout (especially leading- and trailing-edge flaps), control system considerations, wind-tunnel, and CFD methods (see Refs. 12 and 14–17).

2) Within the realm of computational methods, define the appropriate linear and advanced CFD codes for analysis. Define the sophistication required at various stages (initial span loading characteristics to final three-dimensional detailed predictions of separation characteristics). (see Refs. 3, 5–7, 12, and 15).

3) From experimental and CFD approaches, define and assess candidate figures of merit for the prediction of wing drop and wing rock (see Refs. 8 and 15).

4) Develop a relatively low-cost, rapid-access wind-tunnel approach that combines the use of conventional models and static-force test apparatuses to evaluate transonic performance, stability and control, and wing-drop tendencies (using the free-to-roll approach) in a single tunnel entry (see Refs. 10, 14, and 17).

5) Define the impact of unsteady aerodynamics on wing-drop characteristics (see Refs. 4 and 5).

6) Develop guidelines and criteria for the acceptable level of wing drop/rock from a current perspective of weapon systems and future piloting tasks (see Refs. 11, 13, and 16).

7) Define the mathematical modeling required for valid simulation of wing-drop events in piloted simulator studies (see Refs. 13 and 16).

8) Develop parameter-identification analyses and appropriate maneuvers to determine aerodynamic characteristics during flight near and in conditions of uncommanded lateral motions.

9) Incorporate the effects of rigid-body vehicle motions (wing drop and rock) into CFD codes, and use such codes to predict roll damping.

10) Using experimental and CFD tools, expand the meager database for transonic lateral dynamic derivatives for high-performance aircraft.

Conclusions

Many specific airplane types of the past that displayed uncommanded lateral motions at transonic conditions have been identified. References that provide descriptions of the flight observations, time histories of motions, and approaches used to analyze and resolve the problem after discovery are available. A limited number of documents include aerodynamic data.

A common theme has arisen from this review: the problems encountered in flight were generally not predicted or anticipated based on state-of-the-art ground tests or analysis. Although many of the principal factors, such as asymmetric wing stall and its associated rolling moments, fluctuating shocks, and loss of aerodynamic roll damping were known, the lack of a focused effort to correlate and validate ground and flight technologies had not been accomplished. These situations led to expensive, high-visibility, cut-and-try attempts to resolve the problems in flight, where detailed understanding and subsequent contributions to progress in predictive methods is very difficult.

Prior to the Abrupt Wing Stall Program, the state of the art for identifying, analyzing, and eliminating uncommanded lateral motions (especially in early design stages and before flight tests) was extremely poor. Several noteworthy research activities have been identified in experimental aerodynamics, test techniques, and analysis of flight data. Lessons learned from the past experiences should be coupled with the emergence of powerful computational-fluid-dynamics methods to accelerate the state of the art in this area.

Acknowledgments

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