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Flight-Test Assessment of Lateral Activity

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During a developmental flight test of the F/A-18E/F Super Hornet, uncommanded rolling motion was experienced while conducting maneuvers at transonic speeds. Abrupt, large-amplitude lateral events, referred to as wing drop, impaired the pilot's ability to effectively perform air-to-air tracking tasks at these flight conditions. A modified leading-edge flap schedule and the addition of porosity in the wing fold area eliminated the problem. However, finding the solution was slowed by the lack of a validated figure of merit to correlate with computational fluid dynamics, wind-tunnel, or flight-test analysis. A method has been developed to assess lateral activity using flight-test data. The lateral activity assessment involves both qualitative and quantitative evaluations. The pilot performs the qualitative evaluation, and the quantitative evaluation is based on analysis of roll rate, roll acceleration, lateral stick position, and bank angle. This technique provides a reliable approach to assessing lateral activity levels from flight test. An excellent correlation was attained between the pilots qualitative evaluation and the quantitative flight-test data assessment.

Introduction

NUMEROUS high-performance aircraft have experienced adverse lateral characteristics during flight test to expand the flight envelope.[1] The terms wing drop, roll-off, wing rock, and heavy wing describe typical lateral events observed by the pilots. Performance of precision controllability tasks including air and ground tracking missions is degraded when these characteristics are present.[2] They are commonly corrected through wing or flight controls modifications. However, characteristics on some aircraft could not be corrected and imposed operating limitations.

The Super Hornet experienced uncommanded lateral events during envelope expansion flight test. Because of the unexpected, unbounded nature of the roll, pilots termed the motion "wing drop." Wing drop was found to occur most frequently in flight while slowly increasing angle of attack. The aerodynamic flow mechanism for wing drop was an abrupt wing stall, which is described in Ref. 3. A flight controls modification increased the scheduled leading-edge flap deflection at flight conditions coincident with wing drop and provided an 80% solution to the problem.[4] This degree of improvement was sufficient to continue envelope expansion, but the pilots felt that further improvement was warranted prior to completion of the developmental flight-test program. As various wing modifications were evaluated, the pilots reported an assortment of uncommanded lateral events including wing drop, roll-off, wing rock, and heavy wing. The generic term "lateral activity" encompasses all of these uncommanded rolling motions. The incorporation of a porous wing fold fairing eliminated wing drop, and the pilots regarded the residual lateral activity levels as acceptable. Reference 4 provides a detailed summary of the flight-test program to eliminate wing drop on the Super Hornet and discusses the flight controls and wing fold fairing modifications.

One of the primary challenges during the Super Hornet wing-drop flight-test program was the limited role that engineering data played in both the day-to-day decision making and the evaluation of the effectiveness of flight-test modifications. No validated figure of merit existed to quantify lateral activity levels, identify flight conditions exhibiting significant lateral activity, and substantiate pilot comments. The techniques employed during the test program proved adequate in identifying large wing-drop events but struggled with accurately assessing more subtle forms of lateral activity. In addition, the engineering data offered minimal insight into the effectiveness of wing or flight controls modifications. Changes that were judged by pilots as major improvements to lateral flying qualities exhibited only subtle enhancements in engineering data comparisons. For example, the pilots felt that increased leading flap deflection significantly reduced lateral activity levels, but the engineering data showed only a small reduction in overall levels. The identification of minor improvements noted by the pilots was virtually impossible. Because of the lack of correlation with pilot comment, the engineering data were relegated to a secondary role relative to the pilot assessments in evaluating the effectiveness of modifications.

NASA Dryden Flight Research Center studied lateral activity and buffet at transonic flight conditions in the late 1970s with the YF-15, YF-16, and YF-17. Their studies identified a lateral activity assessment technique based on air-to-air tracking tasks. This method utilized measurements of the tracking error derived from cockpit video of the head-up display and target aircraft.[2] An obvious advantage to this approach is the clear operational relevance of both the maneuver and the key engineering figure of merit, tracking error. A disadvantage to this technique is that the instrumentation required to perform the analysis is not standard for all test aircraft including the Super Hornet. In addition, evaluation of typical flying qualities data parameters is difficult during air-to-air tracking because the behavior of the test aircraft is highly dependent upon the maneuvering performed by the target aircraft. This lack of repeatability proved unacceptable for engineering analysis. As a result, the air-to-air tracking task was not deemed suitable for this study.

A thorough review of the engineering analysis performed during the Super Hornet wing-drop flight-test program was conducted to develop a reliable technique for assessing lateral activity characteristics in flight. The ground rules that follow were defined to ensure both the reliability and ease of incorporation of the technique:

1) The method must accurately assess all types of uncommanded lateral activity including wing drop, roll-off, wing rock, and heavy wing.

2) The method must correlate well with pilot evaluations.

3) The method must utilize traditional flying qualities instrumentation. For example, air data, inertial navigation system measurements, control surface deflection measurements, and pilot control inputs are available on typical flight-test aircraft.

This paper details the flight-test lateral activity assessment methodology developed from this review. Evaluation of Super Hornet flight-test data using this technique successfully discriminates between the effectiveness of various wing/flight controls modifications and exhibits an excellent correlation with pilot evaluations.

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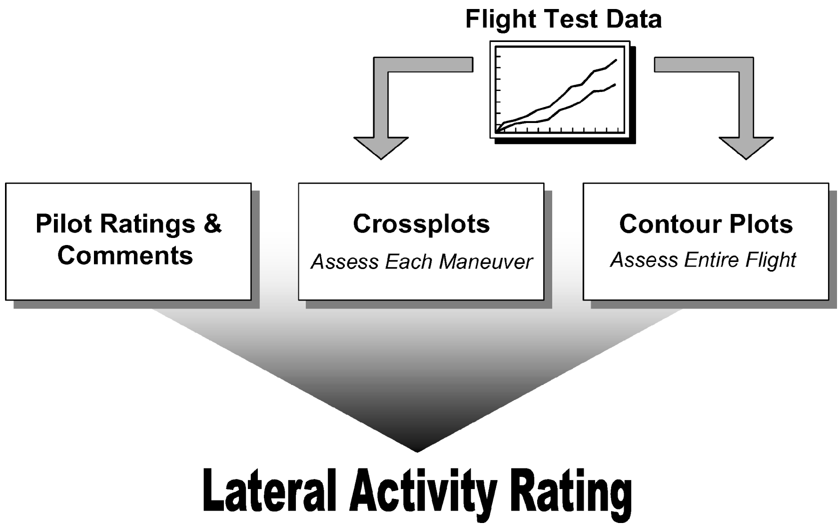

Fig. 1 Approach to lateral activity assessment.

Approach to Lateral Assessment

The lateral activity assessment, depicted in Fig. 1, includes both qualitative and quantitative evaluations. The pilot performs the qualitative evaluation by providing ratings of individual maneuvers and general comments regarding the overall performance of the aircraft during the flight. The quantitative evaluation is based on engineering analysis of four data parameters measured on the aircraft: roll rate, roll acceleration, lateral stick position, and bank angle. Root-mean-square calculations are performed on roll rate, roll acceleration, and lateral stick position. Two engineering analyses are performed using the rms measurements and bank-angle signal.

1) The crossplot analysis examines each maneuver individually. Based on the magnitude of the four measurement signals just listed, an engineering rating is assigned to each maneuver, which can be compared to the pilot rating. This correlation helps establish confidence in the engineering data and can be used to identify maneuvers where the pilot might be responding to other factors.

2) The contour plot analysis reviews the rms roll rate and rms roll acceleration signals from each flight as a function of Mach number and angle of attack. The contour plots provide a detailed engineering picture of where lateral activity occurs in the flight envelope and what the maximum intensity levels are.

The qualitative and quantitative evaluations are used concurrently to assign an overall lateral activity rating for the flight.

Definition of Flight-Test Maneuver

The success of any flight-test evaluation begins with the definition of the maneuver that the pilot must perform. A clearly defined maneuver whose purpose and procedure are thoroughly understood by both the pilot and engineer yields the most repeatable pilot evaluations and engineering data. It is imperative that the flight-test maneuver simulates, at least to some extent, the task to be evaluated.[5] Lateral activity degrades air-to-air tracking performance, and, therefore, a maneuver that involved or simulated this type of task was required. As stated earlier, the air-to-air tracking maneuvers were not repeatable and proved unacceptable for engineering analysis. Wind-up turn maneuvers were identified as the best candidate for flight test.

For this study, a wind-up turn maneuver that met the ground rules for the assessment methodology and operational relevance was defined. A detailed description of the maneuver is provided here:

1) The wind-up turn is to be conducted as a steady pull from 1-g level flight with a slow 1-deg/s angle-of-attack (AoA) onset rate. The turn should be terminated at a maximum angle of attack that exceeds the region of interest by several degrees.

2) The pilot should sustain the target Mach number within ± 0.02 until the maximum allowable load factor is reached.

3) If the maximum allowable load factor is reached prior to attaining the maximum AoA, the pilot should transition to a wind-down turn where Mach number is sacrificed in order to continue increasing angle of attack.

4) As angle of attack increases, the pilot will establish and attempt to maintain a bank angle. The bank angle must be established prior to reaching flight conditions coincident with lateral activity.

5) The pilot is expected to attempt to counter any uncommanded lateral activity such that the bank angle can be maintained.

This definition for a wind-up turn maneuver evolved as a joint effort between the flight-test and aerodynamics teams during the Super Hornet wing-drop flight-test program. The piloting technique for executing the turn was proven to be very repeatable. Maintaining the aircraft bank angle during lateral activity simulates an operational task that the pilot can reliably judge. Although this task is not as operationally relevant as air-to-air tracking, the use of this wind-up turn maneuver permits the engineer to evaluate lateral activity levels using typical flying qualities measurements. The pilot ratings and engineering data will be discussed at length in the sections that follow.

Evaluation of lateral activity with various modifications required that maneuvers be flown at a consistent set of flight conditions. Lateral activity levels can be sensitive to flight condition and flap schedule, so that engineering data analyses are most consistent when common test conditions are compared.

Pilot Ratings

Following each wind-up turn maneuver, the pilot was asked to assign a rating to describe the lateral activity encountered. Traditionally, the Cooper–Harper rating scale is used to qualitatively evaluate aircraft handling qualities. However, the Cooper–Harper rating scale was deemed unsuitable for assessing lateral activity during the Super Hornet flight-test program.[4] The pilots experienced difficulty assigning a Cooper–Harper rating because the aircraft flying qualities changed dramatically over the course of the wind-up turn. Flying qualities were given excellent Cooper–Harper ratings except over the limited angle-of-attack region where lateral activity was experienced. In these regions, the Cooper–Harper ratings were significantly degraded. The resulting pilot ratings exhibited a great deal of scatter and were difficult to interpret.

To rectify this situation, the pilots and test team cooperatively developed a "stoplight" rating system that focused entirely on the lateral activity levels encountered during the maneuver. Using this system, the pilots assigned a lateral activity stoplight rating of green, yellow, or red following each maneuver. Detailed descriptions of the stoplight ratings are provided in Table 1.

Table 1 Lateral activity stoplight definitions

Pilot rating	Description
Red	Lateral activity that shows an abruptness or magnitude such that mission performance would be clearly degraded at that specific flight condition. The aircraft's trajectory is positively affected. This rating includes roll-offs that could not be countered promptly by small lateral stick deflections.
Yellow	Lateral activity whose abruptness and magnitude permits the pilot to use a small, brief control input to either prevent or promptly correct perturbations to the aircraft trajectory. Borderline RED/YELLOW events can be assessed as YELLOW if they are infrequently encountered. This category includes any wing drops, which could be countered promptly by small lateral stick deflections.
Green	Lateral activity either does not exist or is considered inconsequential to the mission.

Description of Engineering Measurements

The lateral activity engineering analysis relies on measurements of four key aircraft parameters: roll rate, roll acceleration, lateral stick position, and bank angle. The roll rate, roll acceleration, and bank-angle measurements quantify the aircraft motion associated with a lateral event. The lateral stick position quantifies the pilot's response to that event. Other parameters were evaluated during this study but did not correlate as well with the pilot comments and ratings. These parameters included angle of sideslip, lateral load factor N_y, roll jerk (derivative of roll acceleration), and the differential control surface deflections.

RMS calculations are performed on the roll rate, roll acceleration, and lateral stick position. The rms roll rate and rms roll acceleration parameters reflect the magnitude and abruptness of lateral activity. The rms lateral stick parameter defines the size of control inputs required by the pilot to counter lateral events. The impact of lateral events on the aircraft trajectory is measured by the bank-angle parameter. Use of the rms calculations was critical to this analysis. These time-averaged signals were found to correlate more closely with pilot comments and ratings than the instantaneous measurements of each parameter. In the instantaneous signals, sizable excursions of brief duration (<0.25 s) tended to skew the engineering analysis. The rms signals minimized the impact of these brief excursions.

RMS calculations were made using a sliding window as shown in Fig. 2. The rms was computed from the instantaneous signal in a 1.0-s window and assigned to the center of the time segment. The window was then advanced 0.1 s, and the rms calculation was repeated.

Maneuver Time Segments

Critical to the success of the lateral activity analysis was the implementation of a consistent technique to select time segments for analysis of each maneuver. The raw flight-test data typically comprise all data from the time the pilot announces the beginning of the maneuver until the aircraft returns to 1-g level flight. This time period includes the roll-in to initiate the wind-up turn and the roll-out at the end of the maneuver. The roll-in and roll-out show up prominently in the rms and bank-angle parameters, and their magnitudes are usually larger than the lateral activity levels encountered during the maneuver. As a result, the maneuver time segments selected for analysis eliminate the roll-in and roll-out from subsequent data processing. The criteria for selecting start and stop times for the lateral activity analysis are depicted in Fig. 3.

Description of Crossplot Analysis

The lateral activity crossplot analysis was developed to provide engineering analysis that correlates with pilot ratings. As discussed earlier, the crossplot analysis provides both an individual maneuver evaluation as well as an overall assessment of lateral activity levels.

The crossplot analysis utilizes the rms roll rate, rms roll acceleration, rms lateral stick position, and bank-angle signals to evaluate the magnitude of the lateral events and the pilot input required to compensate for the lateral activity encountered during each wind-up turn maneuver. Two important assumptions are made in the crossplot analysis. The first assumption is that an ideal wind-up turn has

Equation for Each 1-Second Time Segment

$$RMS = \sqrt{\sum_{t_1}^{t_2} x_i^2 \Big/ N}$$

where

x_i = base signal measurement at time t_i
t_1 = time corresponding to beginning of time segment
t_2 = time corresponding to end of time segment
N = number of samples in the time segment

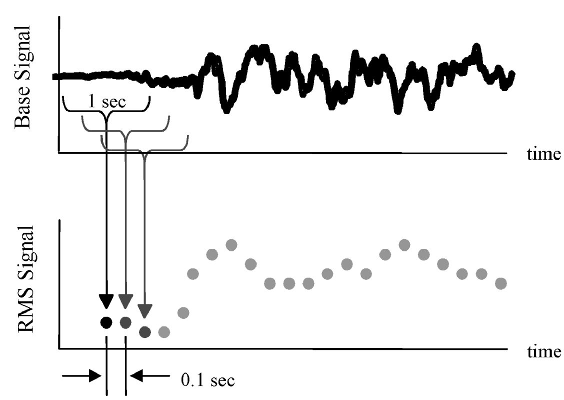

Fig. 2 Schematic representation of rms calculation.

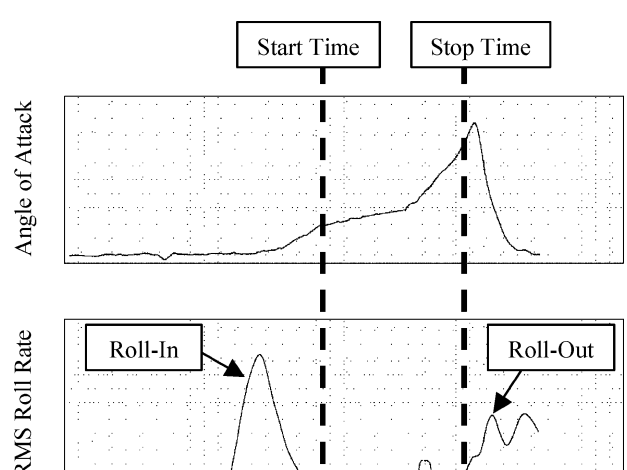

Fig. 3 Example of wind-up turn time cutting.

no uncommanded lateral motion, and no pilot input is required to maintain bank angle. The second assumption is that the pilot rates each maneuver based on the worst lateral activity encountered.

The crossplot analysis quantifies the largest lateral events from the maximum rms roll rate, rms roll acceleration, rms lateral stick position, and bank-angle perturbation encountered during each maneuver. The process for assigning an engineering rating to each maneuver is illustrated in Fig. 4. As an initial data assessment, the maximum rms roll rate and maximum rms roll acceleration are reviewed, and a preliminary stoplight rating is assigned. Lateral activity levels for most maneuvers can be accurately quantified by this evaluation. However, additional criteria are required to check for large bank-angle changes and large lateral stick inputs that also factor into the pilot's rating. Bank-angle and lateral stick criteria can only degrade the stoplight rating assigned by the maximum rms roll rate/maximum rms roll acceleration criterion. The final result of the assessment is an engineering stoplight rating for each maneuver.

Delineations between green, yellow, and red engineering ratings were developed by an evaluation of pilot ratings from 395 wind-up turn maneuvers conducted during the Super Hornet wing-drop flight-test program. This test set consisted of flight data acquired from 22 aircraft configurations and 11 pilots. The crossplot analysis exhibited a 79% correlation between the engineering and pilot stoplight ratings. Figure 5 shows a crossplot of the maximum rms roll rate and maximum rms roll acceleration encountered during each maneuver in the test set. That is, each point on the chart represents the worst lateral event, in terms of rms roll rate and rms roll acceleration, for a single wind-up turn maneuver. The diagonal lines on the chart depict the stoplight boundaries developed for engineering ratings. The orientation of these lines was selected to provide the best correlation with pilot rating. Each symbol is colored to denote the pilot rating assigned to each maneuver. Symbols that are not colored were not assigned a rating by the pilot.

As expected with so many different pilots and configurations, there is some scatter in the pilot ratings. However, the pilot ratings exhibit a clear trend with the rms roll rate and rms roll acceleration parameters. This trend indicates that the pilots primarily rate lateral activity based on the magnitude and abruptness of the events they encounter.

However, the rms roll rate/rms roll acceleration criterion alone was not sufficient to properly assess all types of lateral activity. Slow, sustained roll-offs resulting in large bank-angle changes do not typically exhibit enough roll acceleration to be properly characterized by this criterion. Also, lateral activity that requires very large lateral stick inputs to counter were also rated less severe by this criterion than by the pilot. As a result, two additional criteria were developed to address these types of lateral events and supplement the rms roll rate/rms roll acceleration criterion. The new criteria

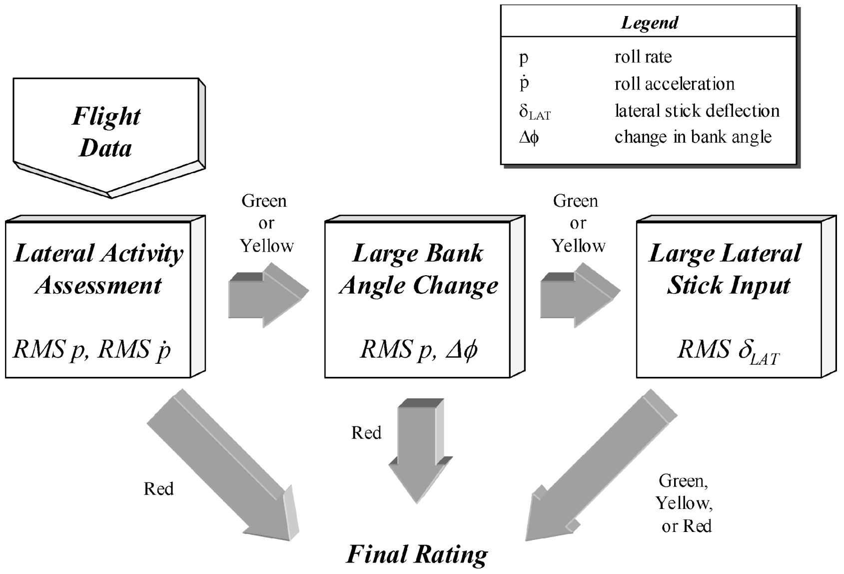

Fig. 4 Lateral activity crossplot analysis flowchart.

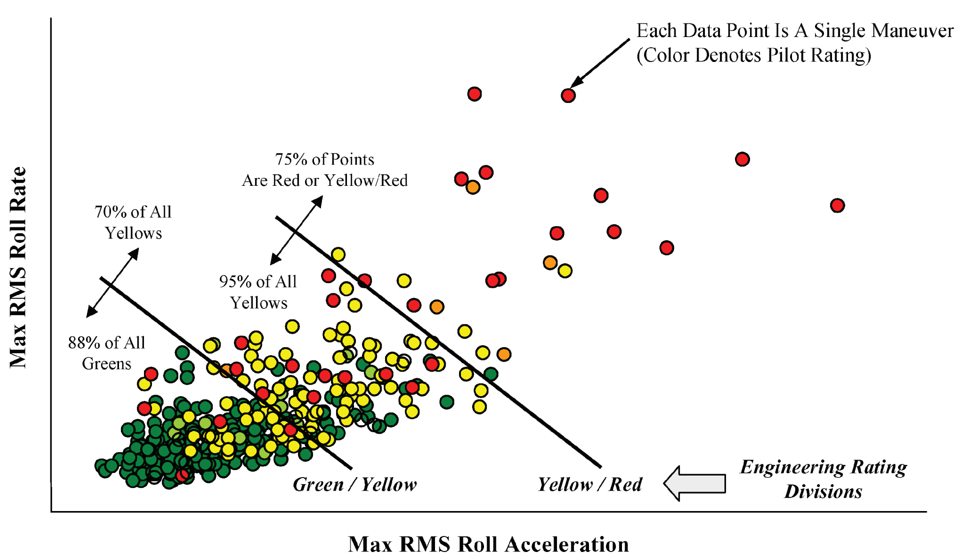

Fig. 5 Crossplot of maximum rms roll rate and rms roll acceleration criterion for test set of 395 F/A-18E/F wind-up turn maneuvers.

were implemented such that they could only downgrade the engineering rating identified by the rms roll rate/rms roll acceleration criterion.

The criterion designed to properly assess slow sustained roll-offs utilizes the maximum rms roll rate and the maximum bank-angle change encountered during each maneuver. Figure 6 shows a crossplot of these parameters for the test set of 395 maneuvers. It is important to reiterate that this criterion was developed to downgrade the engineering rating assigned by the rms roll rate/rms roll acceleration criterion if necessary. As a result, the yellow and red rating boundaries were drawn conservatively to ensure excellent correlation with pilot rating.

A criterion was also developed to evaluate lateral events resulting in large lateral stick inputs. Based primarily on pilot comment, the maximum rms lateral stick deflection permitted to counter a lateral event was defined. Maneuvers exhibiting lateral stick deflections greater than this value are rated red.

In addition to rating each maneuver, the crossplot analysis can be used to evaluate the overall lateral activity levels for a configuration as shown in Fig. 7. For most maneuvers, the engineering rating is assigned based on the maximum rms roll rate and maximum rms roll acceleration. A crossplot of these two parameters provides a summary of the lateral activity levels for a configuration. Test points rated by criteria other than the maximum rms roll rate and maximum rms roll acceleration are appropriately flagged on the crossplots. For this example, configuration B clearly exhibits lower levels of lateral activity than configuration A.

Description of Contour Plot Analysis

The contour plot analysis was developed to provide a more global view of lateral activity levels encountered during an entire flight. As shown in Fig. 8, the contour plots depict rms roll rate and rms roll acceleration as a function of angle of attack and Mach number. In particular, these plots can be used to evaluate flight conditions corresponding to the onset of lateral activity and flight conditions for the maximum intensity of lateral activity. They can also be used to quantitatively compare lateral activity levels for different configurations.

To generate a contour plot, the rms roll rate and rms roll acceleration data from all maneuvers in a flight are sorted into Mach/AoA buckets. The maximum value in each Mach/AoA bucket is displayed on the contour plot at the center of the bucket. As a result, the contour plots depict a worst-case scenario for lateral activity levels encountered during a flight. The colors for the contours were selected to loosely correlate with the stoplight ratings.

Integration of the contour data for a specific angle of attack and Mach-number range allows a quantitative comparison between configurations. To integrate the contour data, the rms values at each grid point are summed for the angle of attack and Mach-number region that ranges from the minimum Mach bound M_0 to the maximum Mach bound M_f and from the minimum angle-of-attack bound α_0 to the maximum angle-of-attack bound α_f. The lateral activity effectiveness of a particular configuration can then be determined relative to another configuration by simply comparing the integration results. That is, the integration results for a particular configuration can be

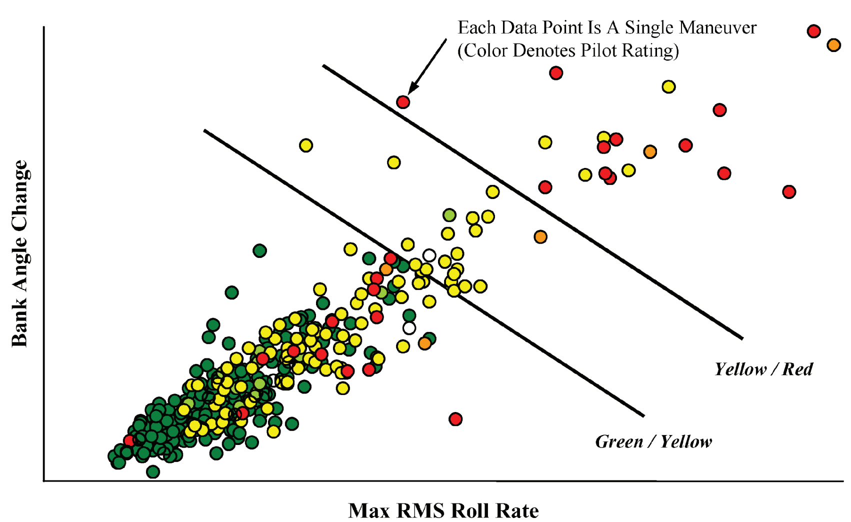

Fig. 6 Crossplot of maximum bank-angle/rms roll-rate criterion for a test set of 395 F/A-18E/F wind-up turn maneuvers.

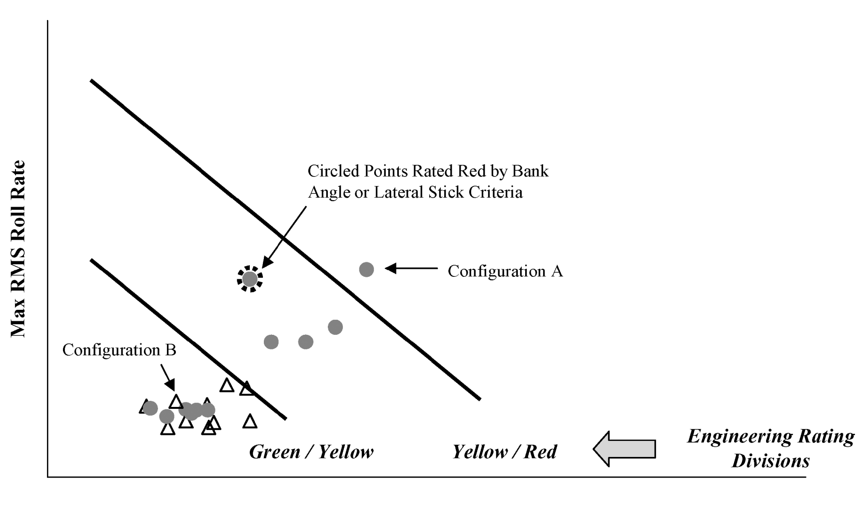

Fig. 7 Example comparison crossplot to evaluate configuration effectiveness.

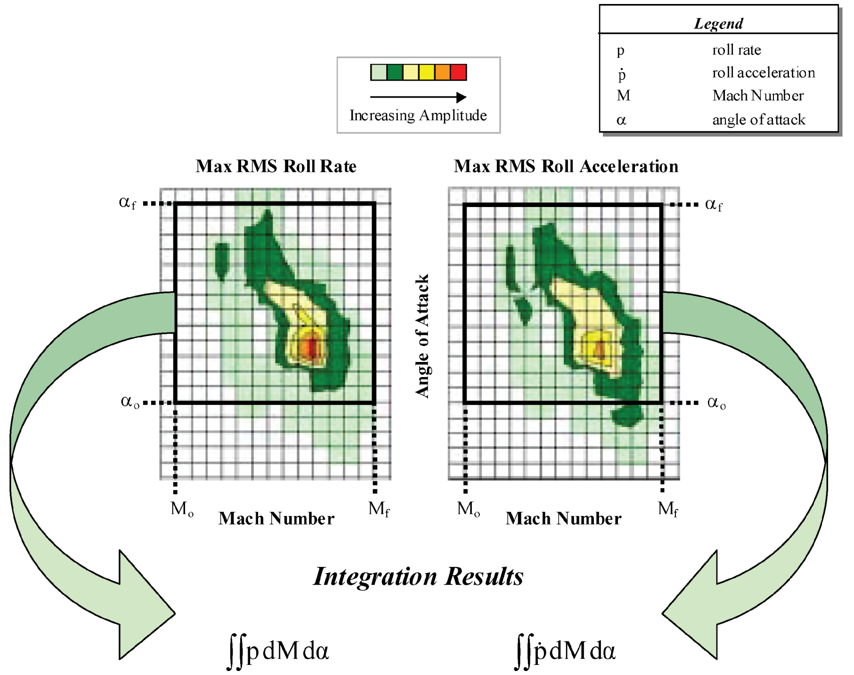

Fig. 8 Example contour plots.

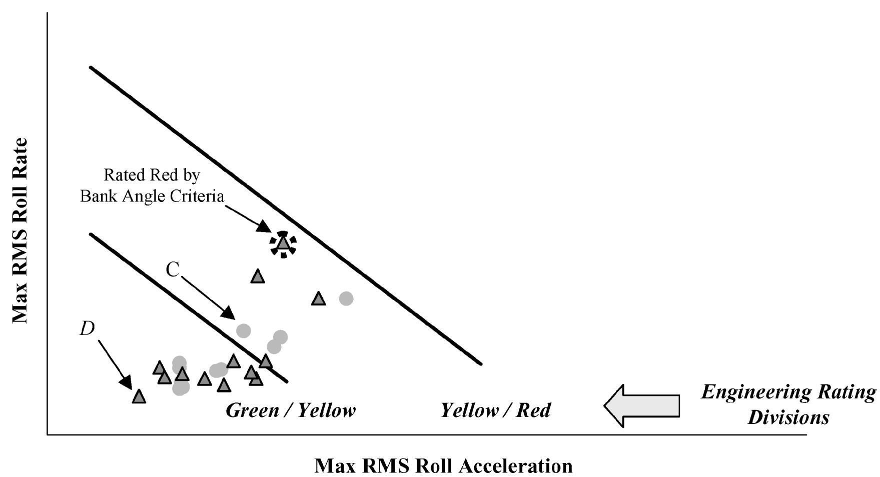

Fig. 9 Crossplot comparison of F/A-18E/F configurations C and D.

normalized by results from another configuration to determine the relative effectiveness.

Application of Technique

To better illustrate the utilization and features of the lateral activity assessment methodology, consider results from two Super Hornet flight test configurations. Configurations C and D were tested at the same set of flight conditions. Figure 9 shows the crossplot comparison for the configurations.

The distribution of data points in Fig. 9 reveals that configuration D exhibits higher lateral activity levels than configuration C. Three fairly large lateral events were encountered with configuration D. One of those events resulted in a red engineering rating for the maneuver.

Configuration C has only one maneuver with lateral activity levels in this vicinity. This analysis is consistent with the pilot's overall assessment of the two configurations. The pilot felt that configuration D produced a few larger magnitude lateral events that were not present with configuration C. For the rest of the test points, the pilot felt that configurations C and D performed similarly. In addition, the pilot ratings for each maneuver correlated well with the engineering ratings for both configurations. For configuration C, a pilot rating correlation of 82% was achieved while an 85% correlation exists for configuration D.

Contour plots for configurations C and D are presented in Figs. 10 and 11. The contour plots echo the overall results from the crossplots. Clearly, a cursory review of the contours shows higher peak rms roll-rate values in a couple of regions with configuration D. Overall, the integration results for configuration D relative to configuration C show a 28% increase in the rms roll rate for the same Mach/AoA envelope. The rms roll acceleration integration results for the two configurations were similar.

Following the configuration D flight, the pilot noted that he thought that the onset of lateral activity was significantly delayed in angle of attack relative to configuration C. This characteristic is evident in the contour plots. The difference in the lateral activity onset angle of attack between configurations C and D is highlighted in Figs. 10 and 11. The onset of the yellow contours for configuration D occurs at a higher angle of attack than for configuration C and was similar in magnitude to the delay described by the pilot.

Based on both the engineering data analysis and pilot comment, configuration D was judged to have a slight degradation in lateral activity levels relative to configuration C.

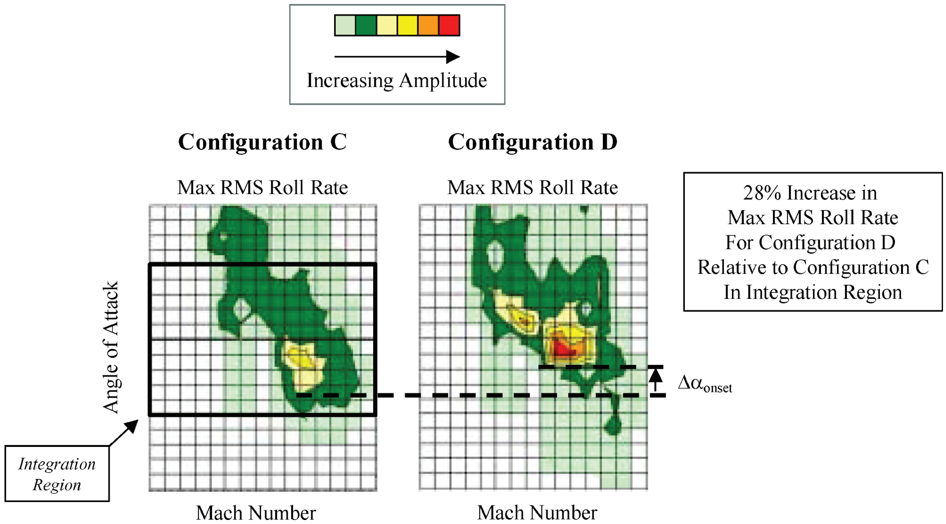

Fig. 10 Maximum rms roll-rate contour comparisons of F/A-18E/F configurations C and D.

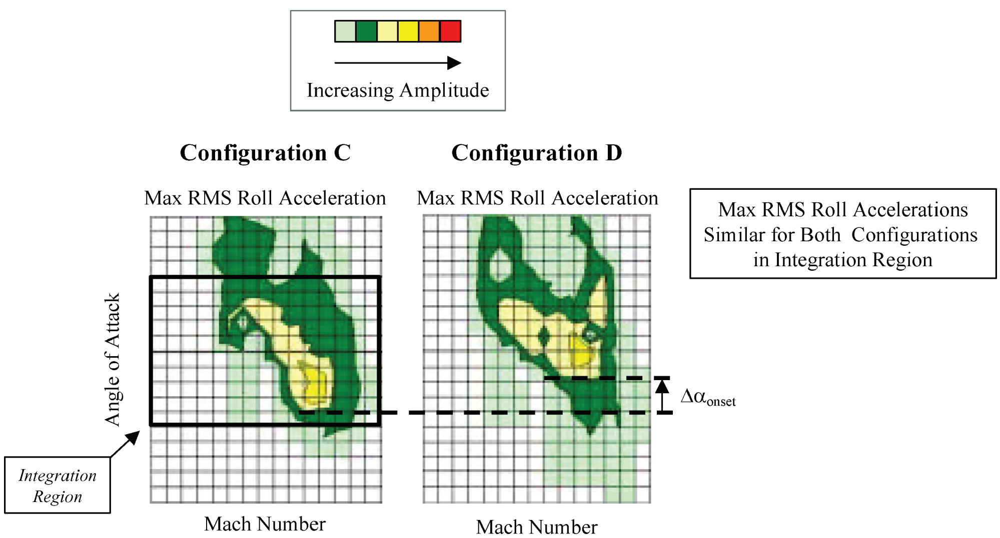

Fig. 11 Maximum rms roll acceleration contour comparisons of F/A-18E/F configurations C and D.

Summary

A generic technique was developed to permit an accurate assessment of lateral activity levels encountered in flight. The technique combines qualitative pilot comments/ratings and engineering measurements/comparisons to evaluate lateral activity. The most significant findings from this study were the following:

1) The lateral activity assessment technique provides a reliable approach to quantifying the characteristics of each flight.

2) The technique successfully utilizes standard flight-test instrumentation and test maneuvers to evaluate lateral activity levels.

3) Correlation between the pilot and engineering evaluations for both individual maneuvers and overall flight impressions was very good. The technique has demonstrated that it is well suited to provide engineering guidance to flight-test decisions.

4) The general analysis technique was developed and validated using F/A-18E/F Super Hornet flight-test data. However, the principles of the analysis technique including the key measurements and underlying assumptions are generic and should be applicable to any aircraft. Pilots are likely to respond to the magnitude, abruptness, and trajectory change associated with a lateral event as well as the control input required to counter that event regardless of the aircraft platform.

Acknowledgments

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References

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

[2]Sisk, T. R., "A Technique for the Assessment of Fighter Aircraft Precision Controllability," AIAA Paper 78-1364, Aug. 1978.

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

[4]Traven, R. S., Hagan, J. L., and Niewoehner, R. J., "Solving Wing Drop on the F/A-18E/F Super Hornet," *Proceedings of the Society of Experimental Test Pilots Forty Second Symposium*, Society of Flight Test Engineers, Lancaster, CA, 1998, pp. 67–84.

[5]Ward, D. T., *Introduction to Flight Test Engineering*, Elsevier, New York, 1993, p. 188.