F/A-18A/B/C/D 9G Flight Test Program[1]

Dr. Jennifer Long
Naval Air Warfare Center, Aircraft Division
22176 Elmer Rd., Bldg. 2133, Unit 4
Patuxent River, MD 20670
301-757-4452
longjm2@navair.navy.mil

LT William Koyama, USN
United States Naval Test Pilot School
22783 Cedar Point Road
Patuxent River, MD 20670
301-342-4411 x3202
koyamaws@navair.navy.mil

Abstract--The purpose of the 9g flight test program recently conducted at Naval Air Warfare Center Aircraft Division, Patuxent River, was to investigate the capability of the F/A-18A/B/C/D aircraft for a 9g load factor envelope (a 1.5g increase over current capability). The 9g capability was enabled by a patch to the mission computer software which changed the basic g-limiter function, including the transonic load factor decrement, or "g bucket" function. The flight test had four objectives: to demonstrate component loads less than 100% design limit for the 9g flight envelope; to evaluate vertical tail buffet during 9g maneuvers; to test the functionality of the g-limiter for 9g maneuvers; and to demonstrate satisfactory flying qualities for the 9g envelope. The paper contains a detailed discussion of problems encountered and lessons learned during the flight test.

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1.0 INTRODUCTION

The F/A-18A/B/C/D Hornet is one of the U.S. Navy's high performance fighter/attack aircraft that has found a market with foreign military services. While the U.S. Navy operates the aircraft with a 7.5g positive symmetric load factor limit, some foreign military customers have requested 9g capability, which has some tactical advantages for air-to-air combat. In order to make the aircraft more attractive to foreign customers, the prime contractor (Boeing Military Aircraft Company) has undertaken to provide 9g capability in a portion of the aircraft's flight envelope. The F/A-18A-D 9g flight test program recently conducted at Naval Air Warfare Center Aircraft Division, Patuxent River, had four objectives: to demonstrate component loads less than 100% design limit for the 9g flight envelope; to evaluate vertical tail buffet during 9g maneuvers; to test the functionality of the g-limiter for 9g maneuvers; and to demonstrate satisfactory flying qualities for the 9g envelope.

1.1 Description of the Test Aircraft

The F/A-18A/B/C/D aircraft is a high- performance, twin-engine supersonic fighter and attack aircraft produced by the Boeing Military Aircraft Company, St. Louis (formerly the McDonnell Douglas Aircraft Corporation). The airplane has moderately swept, variable camber, mid-mounted wings, twin vertical stabilizers canted 20 degrees outboard, a spoiler which deploys from the upper aft section of the fuselage between the vertical stabilizers, and wing leading edge extensions mounted on each side of the fuselage from the wing root to just forward of the windscreen. Control surfaces include full-span leading edge flaps, inboard trailing edge flaps, and outboard ailerons on each wing; independently actuated horizontal stabilizers capable of differential deflection, and rudders on the vertical stabilizers. The flight control system is fully augmented; control surface scheduling is performed by dual-redundant digital computers. The aircraft is powered by two General Electric F404-GE-400 augmented turbofan engines, each of which is designed to produce 16,000 lb maximum uninstalled static sea-level thrust. Fig. 1 is a "three view" drawing of the aircraft showing major dimensions.

The test aircraft was F/A-18C138 (i.e., it was the 138th C model off the production line), Navy bureau number

(BuNo) 163985. C138 has been extensively instrumented with strain gauges, and calibrated for static flight loads measurement. For the component loads flight tests, C138 was outfitted with a flight test noseboom for accurate angle-of-attack (AOA) and angle-of-sideslip (AOSS) measurement. A flight test air data computer incorporating the noseboom's pitot-static source-error correction was used for flight test. Noseboom airspeed and altitude were displayed on the pilot's head-up display (HUD). The aircraft also was equipped with the Navy Combat Edge anti-g system.

C138 was instrumented with a number of strain gauges on fuselage structural members, but calibrations did not exist to convert microstrain output to external loads. Loads calibration in the classical sense is a time-consuming and expensive process, because numerous load cases must be applied to the aircraft in a special test fixture. Equations can then be developed via linear regression to relate strain gauge output to external loads. C138's predecessor, F/A-18A4 (the loads airplane for the full-scale development program), had calibrated forward fuselage loads. Since fuselage loads were predicted to be critical for the 9g evaluation, an in-flight calibration of C138's forward fuselage strain gauges was performed by comparing gauge output for similar maneuvers to A4 data. This technique had previously been used for another F-18 program with good results. A similar procedure was performed to calibrate the aft fuselage gauges, but the resulting calibration proved to be too inaccurate to be used. An equation relating aft fuselage loads to stabilator deflection and other parameters was used instead; the same equation had been used for aft fuselage loads on A4 during full-scale development.

Major airframe component loads are not the only consideration when increased load factor capability is enabled; there are many aircraft subsystem components which may be sensitive to inertial loads. In the case of the F/A-18, four inertia-sensitive components were identified as being critical in a 9g flight envelope. The parts were the nose landing gear uplock pawl, the main landing gear uplock arm support pin, the forward fuselage fuel tank 1 floor support clips, and the aft engine mount links. Production changes to make the parts 9g compatible were material changes for the nose and main landing gear components, and structural beef-up of the tank support clips and engine mount links. For this flight test program, only the landing gear components were replaced with 9g compatible parts. In the case of the engine mount links, analysis showed that dual links provided a structural margin of safety of 24% for a 9g inertial load. In the event of failure of a single link, the margin of safety dropped to –7% for the remaining link. Since there was no history of failures of the links in the fleet or at the flight test center, this risk was deemed acceptable for the program. In the case of the fuel tank support clips, analysis showed that under a 9g inertial condition with a full fuel load, clip loads would reach approximately 104% of limit. In order to keep loads below 100% of design limit, at least 150 lb of fuel would have to be burned out of the tank prior to attaining a 9g condition. Since the normal fuel burn sequence empties tank 1 first, it is virtually impossible to violate this condition. However, as a precaution, tank 1 fuel quantity was monitored by the test team during flight to ensure that the condition was met.

1.2 Determination of Component Design Limit Loads

Airframe component design limit loads are determined from static test fairly early in the aircraft design process. The contractor's loads engineers develop a set of design load cases based on wind tunnel data, design load factor, and preliminary flight control law design. In order to show a component good for a certain load, it must be static tested to a level 1.5 times that load without failing. Loads are applied to a static test article which accurately simulates the load paths present in the airplane. If the static test is successful for a given load case, the critical load becomes "design limit load" for that component. The important point is that design limit load does not necessarily represent the maximum load level that a component can withstand. In some cases a component may have structural capacity for loads much larger than design limit load, in which case the component is said to have margin. The word "limit" in this context has nothing to do with material strength, in relation to which the words "limit" and "yield" are often used interchangeably. Design limit load is simply two-thirds the value demonstrated by static test.

1.3 G-Limiter Operation for 7.5g Capability

The Hornet was originally designed to 7.5g throughout the flight envelope. Thus, at any permissible Mach/altitude combination, aircraft component loads should be less than 100% of design limit for 7.5g maneuvers (at gross weights less than or equal to the design baseline of 32,357 lb). The aircraft's flight control system is designed to limit load factor to 7.5g, dependent on gross weight (g-limiter function). At gross weights (GW's) greater than 32,357 lb, the load factor limit is 7.5g x (32,357/GW). (Hereafter, load factors referenced to GW will be designated by "NzW", i.e., the symmetric load factor limit is 7.5g NzW.) Fig. 2, top plot, illustrates the relationship between load factor limit and GW for symmetric maneuvers (symmetric is defined as less than 3/4 in of lateral stick). The load factor limit corrected for GW is called the "load factor reference", or Nzref. Nzref is set by the mission computer (MC) and is truly only a reference value; it is passed to the flight control computer (FCC), which uses it to determine the load factor command limit. The control system schedules control

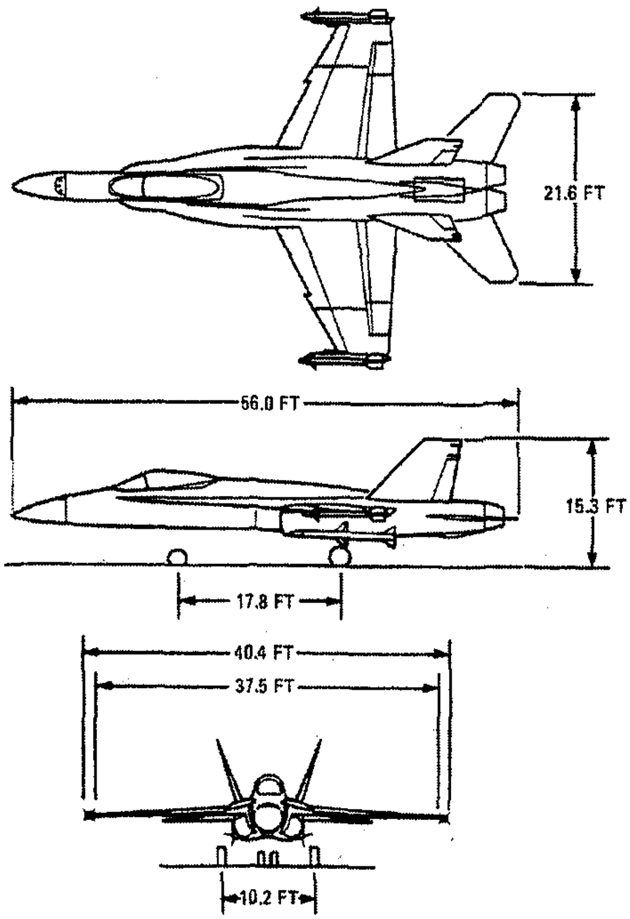


Figure 1
THREE VIEW DRAWING OF F/A-18 AIRPLANE

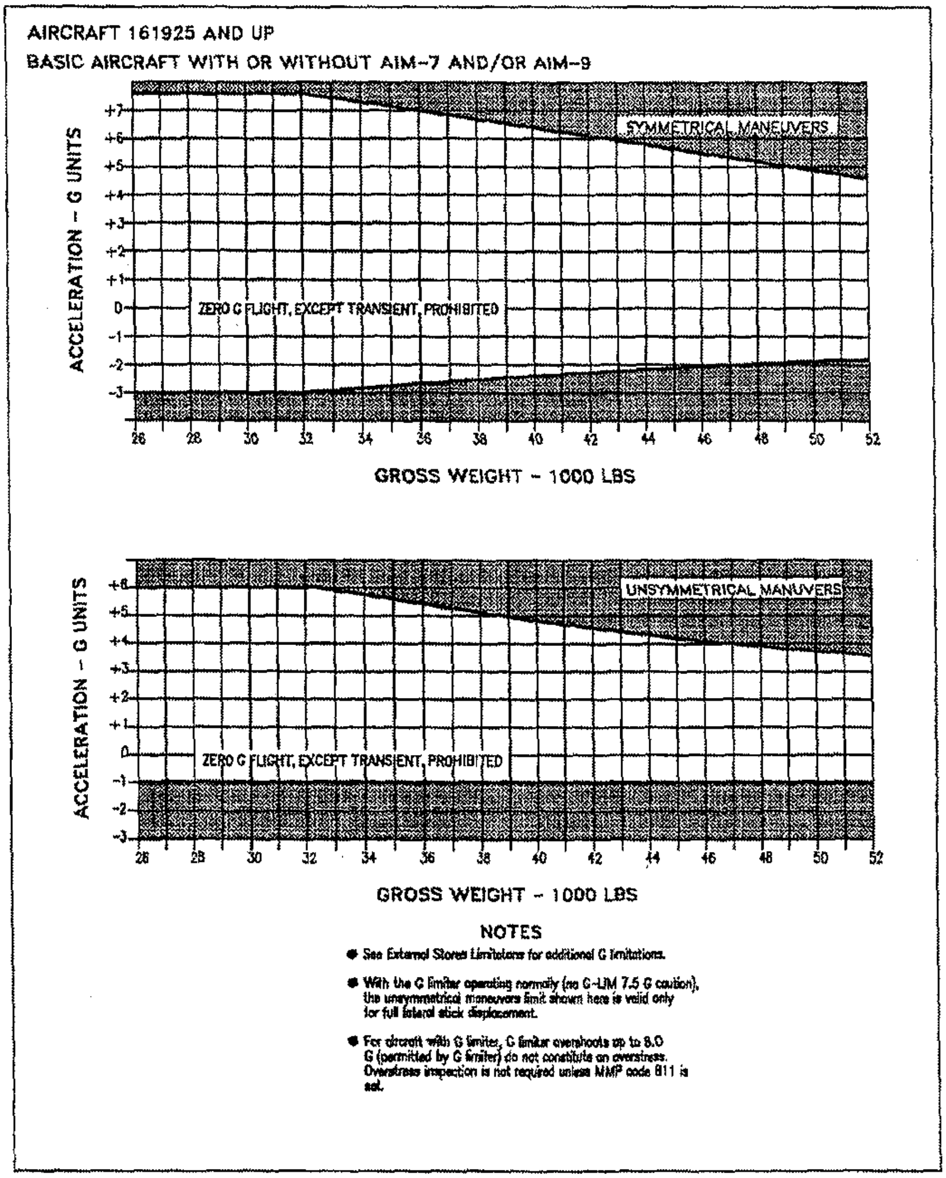


Figure 2
Acceleration Limitations as a Function of Gross Weight

surface deflections to keep load factor below the command limit. Fig. 2, bottom plot, illustrates the relationship between load factor command limit and GW for unsymmetric (rolling) maneuvers. When the pilot inputs lateral stick, the load factor command limit in the FCC decreases linearly from Nzref at neutral stick to 6.0g x (32,357/GW) (or 6.0g NzW, according to the nomenclature used herein) at full lateral stick (3.0 in). This helps to keep component loads below 100% of design limit during rolling maneuvers with smooth lateral stick inputs (smooth being defined as at least one second to full lateral stick). It's important to note that in the 7.5g implementation, Nzref does not change with lateral stick input; only the g command limit changes. The 9g implementation differs slightly, as will be discussed subsequently.

Another area in which the g-limiter protects the aircraft is the transonic region, since load factor transients due to pitch-up may occur as the aircraft decelerates from supersonic to subsonic flight. In order to reduce maximum load factor during pitch-up, Nzref is decremented by 1.0g between approximately 0.88 and 1.08 Mach. This is commonly referred to as the "g bucket". The g bucket logic is tripped when Mach number is greater than 0.95 for the clean aircraft or 0.91 for air-to-ground loadings, but the decrement will be activated only when load factor is within 1.5g of Nzref. The g bucket is automatically deactivated when Mach subsequently falls below 0.88. The minimum load factor limit, including the decrement, is 5.0g, regardless of GW.

1.4 G-Limiter Operation for 9g Capability

In order to enable 9g capability, it was necessary to modify the g-limiter function. The simplest way to do this was by increasing Nzref in the MC, thereby avoiding software changes in the FCC which would require extensive flight test. As in the F/A-18 with 7.5g capability, Nzref is set in the MC and passed to the FCC. 9g capability is dependent on Mach number, store loading, and fuel state. Specifically, 9g is enabled for the clean aircraft with or without empty centerline tank or empty wing tanks, and air-to-air weapons loadings.

Similar to the 7.5g implementation, the 9g implementation has a transonic decrement to protect the aircraft from pitch-up. The MC software used for this flight test program had a "9g bucket", which was implemented as an overlay to the regular g bucket described in section 1.3. The 9g bucket had two reference g values, 9.0 and 8.5g NzW, which were set by Mach number alone. If load factor was within 1.5g of Nzref, the normal g bucket function also was activated, further reducing available load factor via the g command limit in the FCC as discussed in section 1.3.

In the 9g implementation, the load factor command limit was also reduced as a function of lateral stick. However, this was done via a reduction of Nzref in the MC, and the reduced value was passed to the FCC. This is in contrast to the nominal 7.5g implementation, in which Nzref does not change as a function of lateral stick.

2.0 SCOPE OF FLIGHT TEST PROGRAM

Eleven data flights were planned for the test program, including one for instrumentation checkout, seven to evaluate component loads, one for vertical tail buffet evaluation, and two for flying qualities evaluation. Planned weapons loadings are shown in table 1. Loadings 1 and 2 were to be used for component loads evaluation, loading 3 was to be used for the vertical tail buffet evaluation, and flying qualities evaluation was to be performed with loadings 1 and 3. Fourteen data flights were actually flown, thirteen of them in loading 1 and one in loading 2. As will be discussed in detail subsequently, only component loads evaluation was performed, so loading 3 was never used.

The component loads test matrix is presented in tables 2 and 3. The test points were chosen to check high component loads predictions, exercise the g-limiter, and provide a mini-survey of the 9g flight envelope. Wind-up turns (WUT's, banked turns targeting specific g values) were included mainly to check component loads. The rolling pull-outs (RPO's, bank-to-bank rolls at elevated g) were included only to check the logic to reduce load factor with lateral stick input, hence they were restricted to slow inputs (one second to full lateral stick). With abrupt lateral stick inputs, design limit loads could be exceeded for RPO's initiated above 6.0g NzW. The same is true for the baseline F/A-18; the FCC logic to decrease the load factor command limit with lateral stick is only effective for non-abrupt maneuvers. Abrupt pullups (full aft stick at maximum control surface rate) and wind-down turns (banked turn holding target g and allowing Mach to decrease) were included primarily to determine the extent to which the g-limiter would protect the aircraft against high component loads. The 7.5g wind-up turns at 5,000 ft/0.90 and 1.10 Mach were included for in-flight calibration of the forward fuselage strain gauge. The 7.5g wind-up turn at 10,000 ft/1.0 Mach was included for in-flight calibration of the aft fuselage strain gauge.

A flight clearance from Naval Air Systems Command (abbreviated as NAVAIR, the cognizant engineering oversight for Navy aircraft) was required for this testing, since it involved a non-standard aircraft configuration and flight outside the NATOPS (Naval Air Training and Operating Procedures Standardization) flight manual envelope. The flight clearance authorized symmetric maneuvers up to 9.0g NzW, and RPO's at up to 9.0g NzW with slow lateral stick inputs only (slow defined as at least one second to full lateral stick). In the event of load factor overshoot, up to and including 9.5g was authorized without return to base (RTB) and inspection; greater than 9.5 but less than or equal to 10.0g required RTB and a Category I overstress inspection; and overshoots in excess of 10.0g required a Category II

Table 1
TEST LOADINGS

Station	Loading 1	Loading 2	Loading 3
1	LAU-7/CATM-9	LAU-7/CATM-9	LAU-7/CATM-9
2	Clean	SUU-63/LAU-115 CATM-7	Clean
3	Clean	SUU-63/EFT	Clean
4	Clean or LAU-116/CATM-7	Clean or LAU-116/CATM-7	Clean
5	SUU-62/EFT	Clean	Clean
6	Clean or LAU-116/CATM-7	Clean or LAU-116/CATM-7	Clean
7	Clean	SUU-63/EFT	Clean
8	Clean	SUU-63/LAU-115 2 LAU-127 2 CATM-9	Clean
9	LAU-7/CATM-9	LAU-7/CATM-9	LAU-7/CATM-9

CATM = Captive Air Training Missile; -7 = Sparrow, -9 = Sidewinder
SUU-62 = centerline pylon SUU-63 = wing pylon EFT = external fuel tank
LAU-xxx = missile launcher

Table 2
TEST MATRIX FOR LOADING 1

Maneuver	Press. Altitude (ft MSL)	Mach No. (Target/ Actual)	Nz Corr. [1] (g) (Target/ Actual)	Comments
WUT[2]	5,000	0.90/0.90	7.5/8.0	Forward fuselage in-flight calibration
WUT	5,000	1.10/1.08	7.5/7.5	Forward fuselage in-flight calibration
WUT	10,000	1.00/1.00	7.5/7.4	Aft fuselage in-flight calibration
WUT/WDT[2]	30,000	1.40/1.17	8.0/8.2	Build-up for 9.0g
WUT/WDT	30,000	1.40/1.25	9.0/8.6	
WUT	20,000	0.85/0.85	8.0/8.2	Build-up for 9.0g
WUT	20,000	0.85/0.85	8.5/7.8	Build-up for 9.0g
WUT	20,000	0.85/0.77	9.0/9.0	107% TEF hinge moment on third attempt
APU[2]	20,000	0.85/0.85	9.0/8.8	½ and ¾ stick build-ups performed
WUT	20,000	0.92/0.88	Nzmax/8.0	G bucket evaluation
WUT	20,000	0.96/0.90	Nzmax/9.2	Build-up for APD
APD[2]	20,000	0.96/0.96	Nzmax/7.9	G bucket evaluation
WUT	20,000	1.05/1.05	8.0/8.0	Build-up for Nzmax
WUT	20,000	1.05/1.04	Nzmax/8.5	G bucket evaluation/half-stick buildup performed
WUT	20,000	1.15/1.10	8.0/8.3	Build-up for 9.0g
WUT	20,000	1.15/1.13	9.0/8.8	
WUT	20,000	1.20/1.21	9.0/8.9	
WUT/WDT	20,000	1.40/1.25	9.0/9.0	94% wing root bending
APU	20,000	1.40/1.40	9.0/8.8	½ stick build-up performed
WUT	15,000	1.30/1.27	8.0/8.2	Build-up for 9.0g

Table 2 (cont'd)
TEST MATRIX FOR LOADING 1

Maneuver	Press. Altitude (ft MSL)	Mach No. (Target/ Actual)	Nz Corr. [1] (g) (Target/ Actual)	Comments
WUT	15,000	1.30/1.18	8.5/8.3	Build-up for 9.0g
WUT	15,000	1.30/1.20	9.0/8.8	
WUT	15,000	0.85/0.85	8.0/8.0	Build-up for 9.0g RPO
WUT	15,000	0.85/0.84	8.5/8.5	
WUT	15,000	0.85/0.83	9.0/8.8	
WUT	10,000	0.85/0.85	8.0/8.2	Build-up for 9.0g
WUT	10,000	0.85/0.88	8.5/8.6	Build-up for 9.0g
WUT	10,000	0.85/0.86	9.0/9.0	
APU	10,000	0.85/0.85	9.0/8.8	½ and ¾ stick buildups performed
WUT	10,000	1.05/1.03	8.0/8.0	Build-up for Nzmax/99% aft fuselage bending
WUT	10,000	1.05/1.07	Nzmax/8.2	G bucket evaluation
WUT	10,000	1.20/1.08	8.0	Build-up for 9.0g
WUT/WDT	10,000	1.20/1.15	8.5	Build-up for 9.0g
WUT/WDT	10,000	1.20/1.19	9.0	95% forward fuselage bending
WUT	5,000	0.85/0.85	8.0	Build-up for 9.0g
WUT	5,000	0.85/0.85	8.5	Build-up for 9.0g
WUT	5,000	0.85/0.86	9.0	
APU	5,000	0.85/0.86	9.0	½ and ¾ stick build-ups performed/111% wing fold bending on full-stick maneuver
WUT	5,000	0.92/0.90	Nzmax	97% aft fuselage bending/96% wing root bending
WUT	5,000	0.96/1.02	Nzmax	G bucket evaluation
WUT	5,000	0.96/0.97	Nzmax	½ and ¾ stick build-ups performed
WUT/WDT	5,000	1.18/1.15	9.0/8.8	95% forward fuselage bending
WUT	2,000	0.85/0.87	8.0	Build-up for 9.0g/99% wing fold bending
WUT	2,000	0.85/0.85	8.5	Build-up for 9.0g/110% wing fold bending
WUT	2,000	0.85	9.0	Deleted to avoid high wing fold bending load
APU	2,000	0.85	9.0	Deleted to avoid high wing fold bending load
WUT	2,000	0.92/0.92	Nzmax	99% aft fuselage bending/96% wing root bending
WUT	2,000	0.96/0.96	Nzmax	G bucket evaluation
WUT/WDT	2,000	1.10	Nzmax	Unachievable with available thrust
RPO[2]	15,000	0.85/0.85	7.5	Smooth full-stick input
RPO	15,000	0.85/0.82	9.0	Smooth half-stick input
RPO	15,000	0.85/0.83	9.0	Smooth full-stick input

[1] Nz Corr. = Measured load factor x (GW/32,357)
[2] WUT = wind-up turn WDT = wind-down turn APU = abrupt pull-up
APD = abrupt pull-down (split-s) RPO = rolling pull-out

Table 3
TEST MATRIX FOR LOADING 2

Maneuver	Press. Altitude (ft MSL)	Mach No. (Target/ Actual)	Nz Corr. [1] (g) (Target/ Actual)	Comments
WUT[2]	20,000	0.85	8.0	Build-up for 9.0g/Not tested
WUT	20,000	0.85	8.5	Build-up for 9.0g/Not tested
WUT	20,000	0.85	9.0	Not tested
APU[2]	20,000	0.85	9.0	Half stick build-up/Not tested
WUT	20,000	0.88	8.0	Build-up for 9.0g/Not tested
WUT	20,000	0.88	9.0	Not tested
APU	20,000	0.88	9.0	Half stick build-up/Not tested
WUT	15,000	0.92/0.92	Nzmax/8.0	
APD[2]	15,000	0.92/0.92	Nzmax/8.5	106% wing fold bending moment
WUT/WDT[2]	20,000	1.30/1.10	7.5/7.3	Build-up for 9.0g
WUT/WDT	20,000	1.30/1.10	8.0/8.2	Build-up for 9.0g
WUT/WDT	20,000	1.30	9.0	Not tested
APU	20,000	1.30	9.0	Half stick build-up/Not tested
WUT	15,000	1.20	8.0	Build-up for 9.0g/Not tested
WUT	15,000	1.20	8.5	Build-up for 9.0g/Not tested
WUT/WDT	15,000	1.20	9.0	Not tested
WUT/WDT	10,000	1.10	Nzmax	Not tested
WUT/WDT	5,000	1.00	Nzmax	Not tested

[1] Nz Corr. = Measured load factor x (GW/32,357)
[2] WUT = wind-up turn WDT = wind-down turn APU = abrupt pull-up
APD = abrupt pull-down (split-s) RPO = rolling pull-out

overstress inspection. The inspection categories are defined by standard Navy maintenance publications; Category I is basically a visual inspection, while Category II is much more involved and includes non-destructive inspection (NDI). Similar criteria were used for component loads exceedances; overshoots up to and including 110% required RTB and a Category I inspection, and greater than 110% required RTB and Category II inspection. In the case of component loads exceedances, Category II inspection criteria were specified by NAVAIR, and were generally limited to the area of the affected component.

3.0 Flight Test Conduct

The overall plan for the flight test program was fairly typical for loads flight test, in that testing started with maneuvers for which critical loads were predicted to be less than 80% of design limit. The exception to this was the in-flight fuselage loads calibration, since high load levels were necessary to obtain a reasonable calibration. Thus the first three test points completed were the WUT's at 5K-ft/0.90 and 1.10 Mach, and 10K-ft/1.00 Mach, so that the fuselage calibrations could be calculated and used to monitor loads for the rest of the test program. Testing then continued with a number of the build-up points in the test matrix, i.e., 8.0 and 8.5g WUT's at 10 and 20 K-ft. It's often considered advantageous to start with test points at 10 K-ft because the aircraft has good sustained turn performance and the altitude is high enough to provide some ejection margin (NATOPS requires ejection passing 6,000 ft if the aircraft is out of control). In this case, simulator work done prior to the start of flight test confirmed that slower g-onset rates would be possible at the lower altitudes, affording a better opportunity for flying qualities evaluation. It's also generally preferable to start with subsonic test points, but since the test matrix for the loads evaluation consisted mainly of supersonic and transonic test points, some of these were flown fairly early in the program. This was especially feasible since predicted loads were low for many of the supersonic test points. Abrupt pull-ups were flown with half and three-quarter stick build-ups to get a feel for the functionality of the g-limiter before going to full back stick abrupt inputs. Once build-ups and preliminary g-limiter checks were performed successfully, testing proceeded in a manner that was most efficient for each flight.

3.1 Trailing Edge Flap Hinge Moment Overload

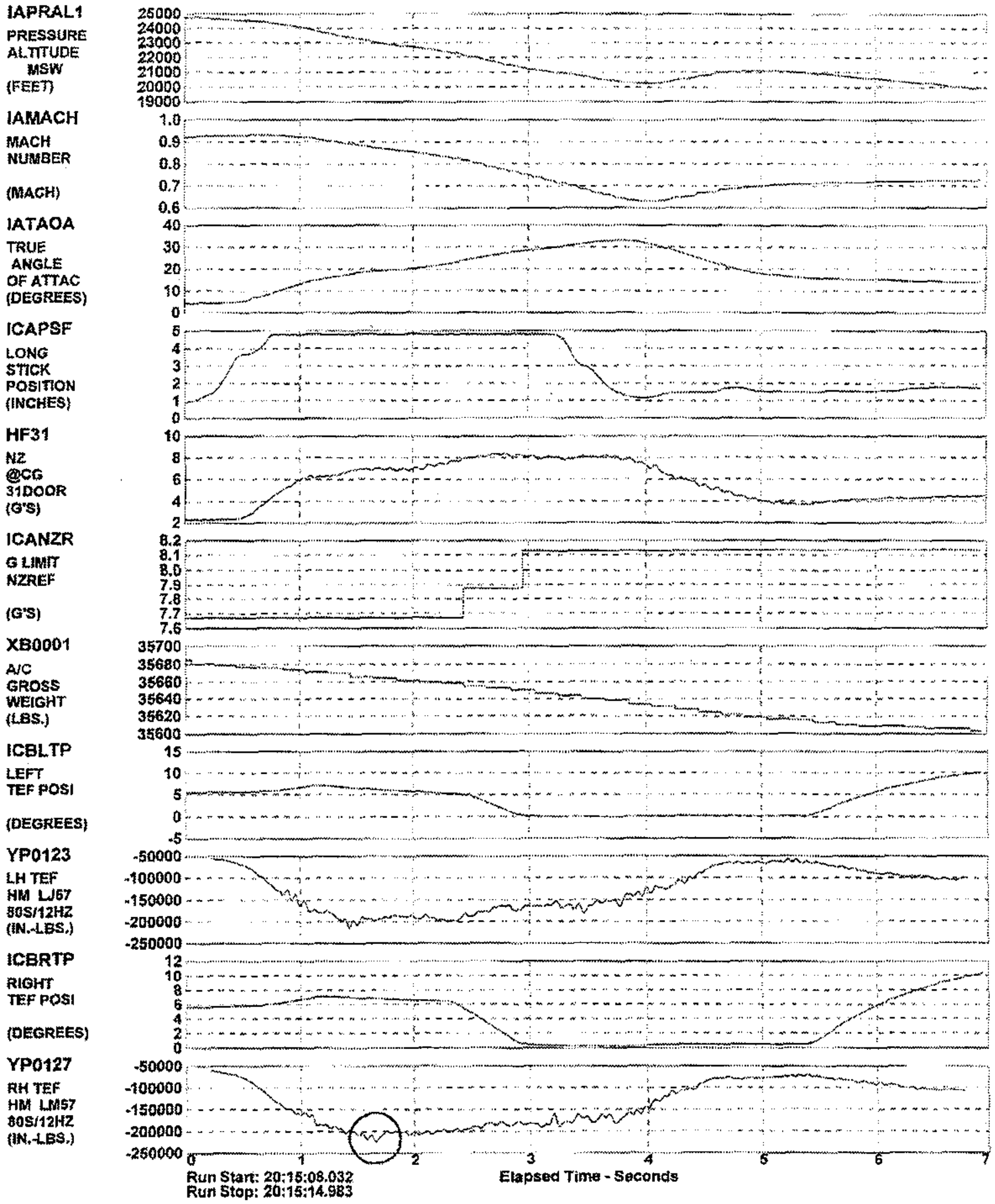
The first component overload occurred during the fourth flight of the test program. The test maneuver was a 9.0g NzW WUT at 20K-ft/0.85 Mach, during which trailing edge flap hinge moment reached 107% of design limit. Fig. 3 shows time histories of various parameters during the maneuver, with the overload circled on the appropriate trace. The design limit load is –210,000 in-lb; the peak load on the plot is about –225,000 in-lb. It's apparent that the load has a dynamic component, with frequency content in the 10 Hz range. The steady-state portion of the load is probably at or below design limit. The trailing edge flap (TEF) load shown in Fig. 6 was filtered to remove frequencies above 12 Hz; the unfiltered parameter has much higher frequency content, and the peak magnitude of the load is on the order of –240,000 in-lb. This raises a question that comes up periodically in loads flight test: should the high frequency peaks count as overloads? Since design limit loads are based on static test, the answer is usually "no", but it is qualified by setting a frequency limit below which the dynamic component is accepted. Normally for F/A-18 component loads flight test the parameters being monitored real time are low-pass filtered to 14 Hz, so any dynamic loads below that frequency count towards test limits.

Dynamics notwithstanding, the static component of the TEF load was close to design limit at this flight condition. This can be explained by an analysis of flap deflection during the maneuver. Flap loads are influenced by angle-of-attack (AOA) and dynamic pressure (q); hence the flight control computer schedules flap deflections as a function of these parameters to keep hinge moments below design limit. The F/A-18A-D TEF deflection schedule for AOA and Mach number is shown in Fig. 4 (there is also a function which limits deflection based solely on q). What's important to note for this example is that scheduled TEF deflection ramps steeply from a fairly high value at moderate AOA's to zero at higher AOA's. If a maneuver is performed such that Mach number and AOA are changing rapidly in the ranges where the flap schedule is steeply sloped, measured flap deflections may not agree with the schedule at all times. In Fig. 3, the peak TEF load occurred at about 0.86 Mach and 19 degrees AOA; according to the flap schedule, TEF deflection should be less than 5 degrees at that condition (positive deflection is trailing edge down). Yet Fig. 3 shows that the flap deflection was on the order of 7 degrees when the overload occurred (a few degrees of flap deflection make a big difference in the hinge moment). The top two time histories in the figure show that Mach was decreasing and alpha increasing during the portion of the maneuver when the overload occurred. TEF deflection didn't start to decrease until about 0.84 Mach and 23 degrees AOA, finally reaching zero at about 0.74 Mach and 29 degrees AOA. Thus flap deflection was quite high during the wind-up portion of the maneuver, which caused a high static component of TEF hinge moment.

It's worth noting that load factor at peak TEF hinge moment was only about 7.0g (7.7g NzW), within the normal design envelope of the Hornet (7.5g NzW + 0.5g for allowable g-limiter overshoot). However, Nzref was almost 7.7g, rather than 6.8g as it would have been with baseline MC software, making it difficult to say whether or not this overload could have occurred with the baseline software. The overload occurred on the third try at this maneuver; the first two attempts were rejected because the target load factor was not achieved at the specified

Figure 3

Time History of Trailing Edge Flap Overload



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Mach number. The first two maneuvers resulted in hinge

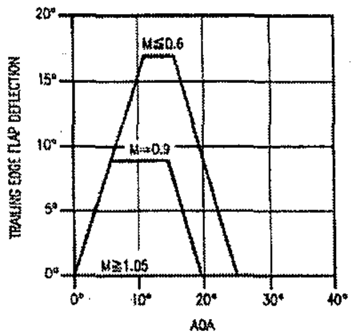


Figure 4

Trailing Edge Flap Schedule as a Function of Mach Number and Angle of Attack

moments which were less than design limit, with nearly identical flight conditions and flap deflections to those which resulted in the overload. The real problem was that the static load was so close to design limit that wing dynamics resulted in an overload. While an occasional small overload is not normally considered to be threatening to the structural integrity of the airframe, cyclic loads at the design limit level could impact the fatigue life of the affected component.

3.2 Wing Fold Bending Moment Overloads

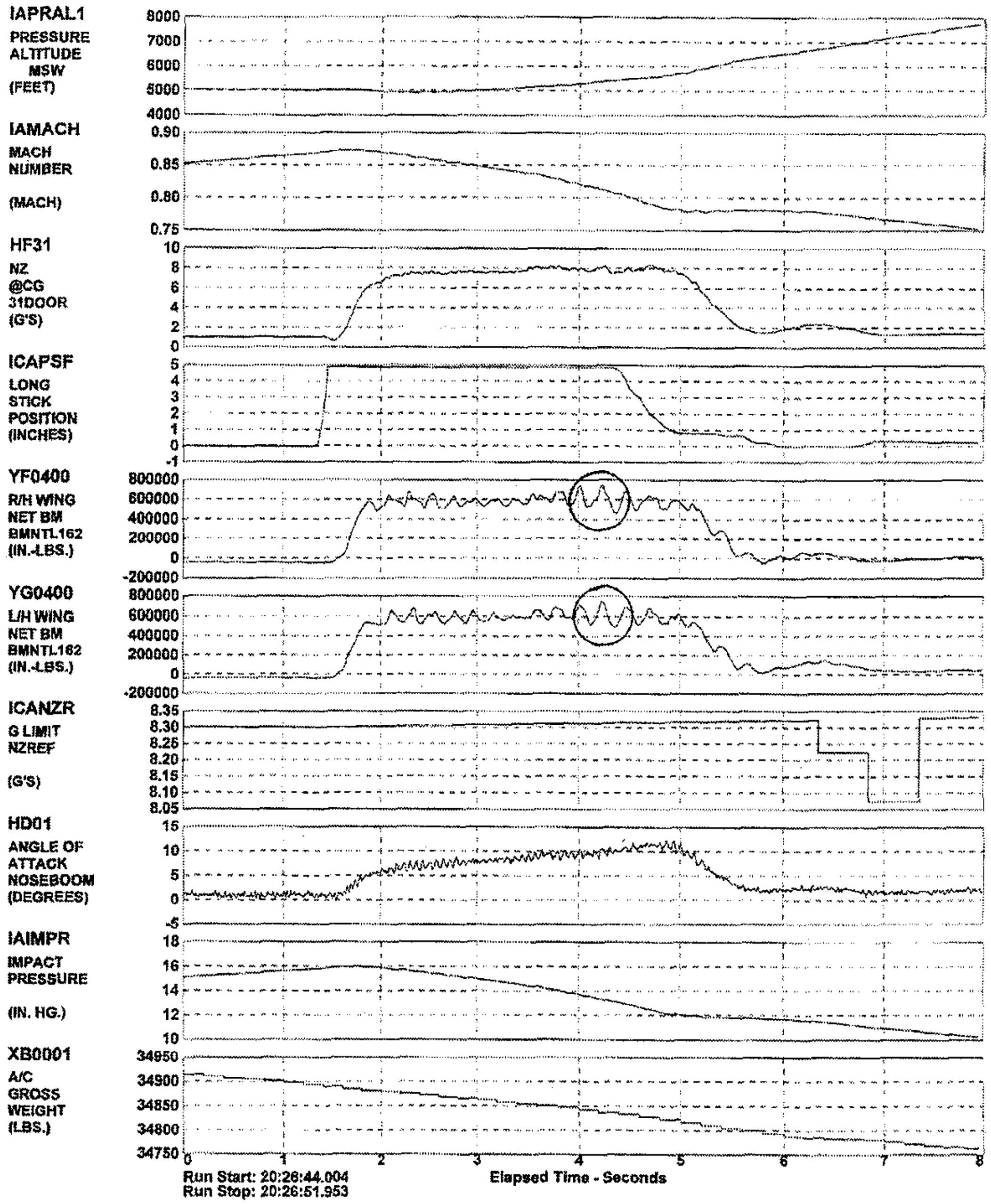
The TEF overload was analyzed by the test team, and a notation to "knock it off" at specific Mach numbers was added to the flight cards for maneuvers where similar occurrences were anticipated ("knock it off", or KIO, is normally relayed to the pilot by the test conductor as a signal to abort the test maneuver). The purpose of this approach was to reduce load factor before Mach number decreased into the range where the overload had occurred. As always, the engineers monitoring loads could make KIO calls directly to the pilot if necessary to prevent an overload. Nonetheless, another component overload occurred during the sixth flight of the test program, when wing fold bending moment (WFBM) reached 111% of design limit during a 9.0g NzW full stick abrupt pull-up at 5 K-ft/0.85 Mach. Fig. 5 shows time histories of several relevant parameters, with the WFBM overload circled on the appropriate traces. As was the case with the TEF overload, the static load was less than design limit (limit is 669,000 in-lb), but the dynamic component was of sufficient magnitude to cause an exceedance. In this case the dynamic component was at a lower frequency (4-6 Hz) than what was seen on the TEF. One of the wing bending modes falls in that frequency range, so it's possible that the mode was being excited by the aerodynamics at these flight conditions.

As shown in Fig. 5, Nzref for this maneuver was 8.3g, which corresponds to 9.0g NzW at the aircraft gross weight shown (approximately 34,900 lb). Since the maneuver targeted 9.0g NzW, the pilot could not exceed 0.9 Mach during set-up because that would have tripped the 9g bucket and reduced Nzref to 8.5g NzW (about 7.9g at this GW). This made it difficult for the pilot to achieve the desired end conditions, since he didn't have the option to start fast and allow Mach to decrease as load factor increased. The pilot held full aft stick for a few seconds because load factor was creeping slowly up towards the target value of 8.3g, although it never actually achieved it. The dynamic component of load peaked suddenly after about 2.5 seconds of full aft stick, at which point KIO was called and the pilot relaxed longitudinal stick. The overload occurred during the second attempt at this maneuver; the pilot had previously performed it with a slower longitudinal stick input than what was desired, resulting in end conditions that were not within test tolerances. The dynamic component of load was smaller on the less abrupt maneuver, although WFBM peaked near 100% of design limit.

Since the load magnitude of 111% of design limit was large enough to require a Category II overstress inspection, a meeting involving the contractor (Boeing), Navy maintenance, the flight test team, the Foreign Military Sales (FMS) program office, and NAVAIR loads and strength engineers was convened to discuss procedure. It was determined that wing buffet is not unexpected at the AOA and dynamic pressure experienced during the maneuver. However, the magnitude of the dynamic component of load was much higher than had been seen during the loads flight tests of the F/A-18 full-scale development program. Given this information, a discussion of how to safely proceed with testing ensued. The contractor and the flight test team took the position that the full test matrix should be attempted in order to thoroughly characterize the effectiveness of the 9g software. However, this would be done with the expectation that overloads might occur even though every effort would be made to keep loads within limits. The test team also requested that the flight clearance be modified to allow testing up to 110% of design limit without RTB, and to require only a Category I inspection for overloads up to 115% of design limit. The distinction between this approach and the original flight clearance was that the original clearance contained provision for accidental overshoot to 110%; it was understood that the test team would not perform test points where loads were expected to exceed 100% of limit. The contractor received an action item to determine the static strength margin over design limit for wing fold bending, and NAVAIR deferred the request to modify the flight clearance pending review of the strength margin data from the contractor. The test team proposed to defer the rest of the subsonic test points until that review was completed, and concentrate on supersonic test points where buffet would not be a problem.

Figure 5

Time History of Wing Fold Bending Moment Overload



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When the analysis of the wing fold strength margin was complete, the result was that there was no excess structural margin in the wing fold area, i.e., yielding was predicted to occur at the 115% design limit load level. Therefore, NAVAIR decided not to amend the existing flight clearance to allow testing up to 110% design limit. The test program continued, with extra build-up added to the test matrix and KIO's briefed in an attempt to avoid the known problem areas for TEF hinge moment and WFBM. Unfortunately, during the twelfth test flight, another WFBM overload occurred during a WUT targeting 8.5g NzW at 2 K-ft/0.85 Mach. Bending moment reached about 110% of design limit. Pre-flight prediction based on the existing loads flight test database and accounting for buffet had anticipated high wing fold loads during this maneuver, and the test engineer monitoring the load made a KIO call when the dynamic component of the load appeared. Unfortunately, the pilot could not reduce aft stick quickly enough to prevent the overload. This event led to a re-evaluation of the feasibility of continuing the test program.

As before, a meeting with the various interested parties was convened, the end result of which was that a decision was reached to continue testing. The proposed plan of attack was similar to what had previously been done: avoid known problem areas by using KIO criteria based on Mach number, delete test points that had a high risk of causing wing fold bending overloads, and make real-time KIO calls based on load levels seen during test maneuvers. However, there was a growing level of skepticism among members of the flight test team about the effectiveness of this approach, since it had not prevented the second WFBM overload. Another concern was the dynamic nature of the load, which made prediction of peak levels impossible given the limited amount of flight test data. The contractor was anxious to continue testing so that the 9g software could be thoroughly evaluated, but some test team representatives were hesitant to risk another incidence of overload, particularly since it was known that the wing fold had very little structural margin over design limit. While these issues were under discussion, the aircraft was undergoing wing fold inspections, and it was discovered that the wing fold freeplay exceeded the value allowed by maintenance publications. Specifically, the maintenance publications require freeplay to be less than 0.57 degrees, while C138's was measured at 0.69 and 0.66 degrees on the left and right wing, respectively.

The freeplay problem quickly escalated into a major issue, since it is technically a downing discrepancy for the aircraft. However, some research into the origin of the freeplay requirement revealed that it was not based on fleet data, but was a somewhat arbitrary number that had originally been proposed by the flutter community. Historical data from fleet airplanes showed that they were more likely than not to be out of tolerance, with the amount of freeplay being somewhat related to the number of flight hours on the airframe. It's not a routine maintenance procedure to measure wing fold freeplay, so it was unknown when C138's freeplay first exceeded the limit. However, C138's freeplay was consistent with fleet measurements for aircraft with similar numbers of flight hours. The major source of controversy was the question of whether or not C138 would be allowed to continue testing without correcting the out-of-tolerance freeplay. While everyone agreed that it would be ideal to fix the freeplay prior to continuing testing, the schedule couldn't accommodate the time required to accomplish the repair. Another problem was that the repair procedure involved removing the outer wing, which would involve extensive work by the instrumentation group to avoid damage to test instrumentation. The general consensus of the cognizant NAVAIR engineers (flutter, loads, and strength) was that in light of fleet historical data on wing fold freeplay, C138's freeplay was not a serious problem, and they were willing to write a waiver of the maintenance requirement. The flight test community agreed to continue testing if a waiver were granted. Navy maintenance recommended against flying with out-of-tolerance freeplay, regardless of the waiver option, since it was a downing discrepancy. The program office expressed doubts about the utility of further testing, but ultimately decided in favor of continuing the testing to give the contractor every opportunity to gather data to adequately characterize the 9g software implementation. Ultimately, a decision was made to continue with the test program with the existing out-of-tolerance freeplay.

The test program recommenced at the end of October 1997. The first flight flown completed the component loads testing in loading 1 (planned maneuvers at 2K-ft/0.85 Mach were deleted to avoid a possible WFBM overload). The next phase of testing was component loads testing in loading 2, which was an air-to-air loading. The precautionary measures previously discussed to avoid TEF and WFBM overloads were implemented, but during an abrupt pull-down targeting Nzref at 20 K-ft/0.92 Mach (this was basically a full-aft-stick split-s to test the g-limiter) wing fold bending moment reached 106% of design limit. Following this incident, the flight test program was terminated on the basis of the high loads, which clearly could not be controlled by conventional flight test risk mitigation techniques.

3.3 MSP 811 Overstress Codes

While the component loads problem was a serious one from the airframe point of view, the 9g software had a minor glitch on the avionics side. The problem involved tripping of the code for aircraft overstress, designated as an MSP 811 (the code is displayed on the maintenance status panel, hence the term "MSP"). The code is tripped when actual load factor is more than 0.5g above Nzref. MSP 811 was tripped during several of the 9g program test flights, even though load factor during symmetric maneuvers exceeded 0.5g above Nzref only once (this was considered an actual aircraft over-g, and hence a "true" MSP 811). It was determined that two scenarios were resulting in false 811 codes. The first concerned fuel slosh in the centerline tank; the 9g logic was automatically disabled when the aircraft sensed more than 60 lb of fuel in the tank. The tank normally contained a small amount of fuel during the flight, because it was partially fueled between flights to allow the test aircraft to start up, taxi, takeoff and transit to the test area without using internal fuel. Unfortunately, maneuvering flight causes the fuel to move around in the tank, which can result in inaccurate fuel weight measurements. There are two possible scenarios relating to fuel slosh for the 9g implementation. One is that the tank actually contains more than 60 lb of fuel, but fuel movement away from the weight sensor causes the weight to register lower than 60 lb, so 9g logic is improperly enabled. The other is that the tank has less than 60 lb of fuel, but fuel movement toward the weight sensor results in an erroneously high weight measured, so 9g logic is improperly disabled. The latter scenario resulted in several MSP 811 codes during the 9g test program. The pilot would pull to Nzref (8.5 or 9.0g NzW), fuel movement would cause the 9g logic to be disabled, Nzref would revert to 7.5g NzW, and the aircraft would register an MSP 811 since actual load factor was more than 0.5g above Nzref. This was apparent to the pilot when it occurred because Nzref would improperly revert to 7.5g NzW.

The second cause of 811 codes was the Nzref decrement with lateral stick. During rolling pullout (RPO) maneuvers at high load factor, even though the pilot input the lateral stick slowly (at a rate of 1 sec to full lateral stick), Nzref would decrement faster than the flight control system could effect a decrease in actual load factor. This resulted in load factors greater than 0.5g in excess of Nzref, tripping the 811 code. 6.0g NzW is the aircraft's unsymmetrical maneuvering limit, but smooth rolling maneuvers at load factors above that level will not necessarily cause component overloads. In this case, component load levels were observed to remain within test limits when the overstress codes were tripped. Similarly, MSP 811 was sometimes tripped when the pilot would make small (0.75 in) lateral stick inputs during WUT maneuvers. Since roll acceleration is negligible for small lateral corrections, the 811 code was definitely inappropriate in those cases. The 811 code is intended to flag aircraft over g; unsymmetrical maneuvering above 6.0g NzW does not constitute an over-g. This problem is unique to the 9g implementation, and occurs because Nzref decrements with lateral stick. In the 7.5g implementation, only the g command limit in the FCC changes with lateral stick. Nzref remains at 7.5g NzW, so the 811 code is not tripped during rolling maneuvers above 6.0g NzW.

3.4 Fuselage Loads

Forward and aft fuselage loads were predicted to be critical for the 9g implementation. Test measured fuselage loads never exceeded 100% of design limit for either forward or aft fuselage bending moment, although loads on the order of 95-99% were seen at some flight conditions. However, fuselage bending is influenced significantly by variables such as aircraft c.g. position and weight distribution, and the test aircraft was not representative of the worst-case configuration for fuselage bending loads. The contractor has developed equations to correct fuselage loads to worst-case c.g. and inertia conditions. When the measured loads from the 9g flight test program were corrected to worst-case conditions, both forward and aft fuselage bending moments exceeded 100% of design limit. This problem didn't affect the flight test program, since the test measured loads were within limits, indicating that the test aircraft wasn't suffering overloads. It would be a problem for clearing the 9g software for general use by a foreign military service. However, based on detailed analysis by the contractor, there was some question about the accuracy of the flight measured loads from the 9g test program. Final resolution of this issue is in work by the contractor.

4.0 Lessons Learned

One observation from these flight tests is that the F/A-18A-D production trailing edge flap schedules do not protect the TEF's from cyclic loading at the design limit level. The TEF has structural margin over design limit, but cyclic loading ultimately results in fatigue damage. The F/A-18A-D fleet has had some problems with TEF failures, which may be related to the cyclic loading seen during these flight tests. The 9g program did not uncover this phenomenon, but provided more data to help NAVAIR diagnose and correct problems in the fleet.

Other lessons learned from the test program are more general. The wing fold bending overloads were surprising in that the magnitude of dynamic load had not previously been seen, but the overloads did occur at load factors outside the 7.5g design envelope where most historical data were gathered. The 9g implementation is a relatively new development for the aircraft, (although some 9g flight test had previously been performed), so there is a very limited flight test database to define the scope of the wing fold bending problem. As a result of the 9g flight data, it's likely that wing fold bending moment will be scrutinized during future flight test programs using C138, even for the 7.5g implementation.

One observation from the struggle with wing fold bending loads is that despite the best of intentions and the most meticulous build-up procedures, overloads can occur. A typical test plan for flight loads evaluation addresses risk mitigation by comparing measured loads to predictions, proceeding in small steps where loads gradients are high, adding build-up real time as required, and calling KIO when loads approach test limits. While all these measures are prudent, they may not be straightforward to implement. Loads predictions typically amount to a single number, i.e., the magnitude of a component load expected during a particular maneuver. This doesn't tell the engineer much about what happened during the maneuver that caused the load. For example, in the 9g test program, wing fold bending loads exceeded predicted levels because the magnitude of dynamic load was unexpected, based on historical loads data. The contractor's dynamics engineers were not at all surprised that the dynamic component of load was present at the critical flight conditions, but since they normally work with data in frequency ranges above what is considered significant for static loads testing, they didn't have a good feel for what magnitude would be expected in the filtered data. This is an example which demonstrates that the usual practice of comparing measured to predicted loads to evaluate trends simply isn't adequate to characterize all the variables that can influence results (and thus should be taken into account in test planning).

Some of the other standard loads flight test techniques can be equally limited in their effectiveness. In an aircraft like the F-18, which is heavily augmented, a very thorough knowledge and understanding of the flight control system and how control surface schedules affect measured loads is required to effectively administer the test program. It's hard to add build-up or understand where loads gradients will be high if you don't know how control surface schedules vary throughout the envelope. Conventional build-up procedures, i.e., high-to-low altitude and low-to-high Mach number, may be inappropriate depending on what is being tested. Simply adding points at intermediate Mach numbers or load factors may not accomplish anything in the way of build-up. Similarly, partial control inputs (half-stick, half-pedal) are not normally useful for predicting what loads for the full input will be, since the loads will not vary linearly with control input. Real-time KIO calls are highly overrated for most loads maneuvers, since test loads change too quickly for human responses to keep up. For abrupt maneuvers, the peak load usually occurs virtually instantaneously with control application. KIO calls are almost always too slow to prevent component load overshoot, or even g overshoot in many cases.

The 9g program demonstrated how standard flight test risk mitigation techniques can be scrupulously applied and still fail to prevent exceedance of test limits. While risk mitigation is a necessary part of the flight test that should always be carried out to the maximum extent possible, sometimes a decision must be made to either complete the testing and accept whatever loads fall out, or to stop testing if overloads are intolerable. The former is generally only feasible if the results of the testing are of paramount importance and the magnitude of potential overloads is such that a flight mishap is highly unlikely. During the 9g evaluation there was some disagreement between the communities involved as to the riskiness of continued testing. The technical community properly tended towards a hands-off approach; they defined test limits, and left it to the test team to develop procedures to keep loads within those limits. The flight test community had perhaps more confidence than was warranted that loads could be kept under control. The maintainers were opposed to any flight activity which posed a risk to the test aircraft; in their view, the riskiness of the testing was proved by the overloads which had already occurred. As engineers, we like to think that there's one "right" answer, but if enough people get involved, the decision-making process can become clouded. In this case the right decision was eventually reached, which was to terminate the test because the 9g software was clearly not able to protect the aircraft from overloads due to dynamics at the wing fold. Of course, the software was never designed to prevent dynamic wing loads, since the historical loads data did not indicate that there was a problem. In actuality, the wing fold loads were a fallout of the testing which unfortunately overwhelmed the basic objectives of the test program.

In conclusion, while the test program was not an unqualified success from the standpoint of clearing the 9g implementation for fleet usage, it did highlight some of the more subtle problems that can be encountered during loads flight test. While stressful at the time (to both the test team and the test aircraft), the flight test was a valuable learning experience for everyone involved. One recommendation is that a very thorough assessment of potential loads problems should be conducted and discussed prior to the start of flight test. The starting point for this assessment is the static loads predictions, but the predictions should not be considered to be the last, best estimate of what will occur during flight test. Test team members should use their knowledge of aircraft response and performance along with the predictions to brainstorm any possible loads problems that could arise, no matter how unlikely they might seem. This technique is used successfully for hazard assessment and mitigation for all types of flight test. Surprises may still occur (that's why we do flight test, after all), but minimizing them will always increase test efficiency and safety, which should be the goal of every test engineer.