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Project MAGIC CARPET: Advanced Controls and Displays for Precision Carrier Landings

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Maritime augmented guidance with integrated controls for carrier approach and recovery precision enabling technologies (MAGIC CARPET) is an enhanced set of flight control laws and Head-Up Display symbology for F/A-18E/F/G aircraft which seek to reduce the unique pilotage skills required for shipboard landings. Integrated Direct Lift Control significantly simplifies 'ball flying' by allowing for repeatable and precise flightpath changes using lift as directly commanded via longitudinal stick displacements. Additionally, 'Delta Path' control mode adds a feature that allows the aircraft to capture, maintain, and return to the 'ideal' 3.5 degree glideslope, nearly hands off. This essentially de-couples the glideslope task from the lineup task. The enhanced HUD symbology provides much improved direct pilot feedback cues on the magnitude of glideslope and lineup corrections. Recent shipboard flight test completed aboard the USS Bush (CVN-77) in April 2015 confirmed a 50% reduction in touchdown dispersion as well as greatly reducing overall carrier approach workload as observed through real-time pilot feedback. Test results, pilot comments and lessons learned will be presented.

Nomenclature

ATC = *Automatic Throttle Command*
CNAF = *Chief of Naval Air Forces*
CVN = *Aircraft Carrier – Nuclear Powered*
CQ = *Carrier Qualification*
DAF = *Dial-A-Function*
DFP = *Delta Flight Path*
DP = *Delta Path*
FCS = *Flight Control System*
FCC = *Flight Control Computer*
FCLP = *Field Carrier Landing Practice*
FPAH = *Flight Path Angle Hold*
HQR = *Cooper-Harper Handling Qualities Rating*
IFLOLS = *Improved Fresnel Lens Optical Landing System*
IDLC = *Integrated Direct Lift Control*
INS = *Inertial Navigation System*
LSO = *Landing Signal Officer*
MFS = *Manned Flight Simulator (NAVAIR – Patuxent River MD)*
MoD = *Ministry of Defence (UK)*
NAE = *Naval Aviation Enterprise*
NWS = *Nosewheel Steering*
ONR = *Office of Naval Research*
SRVL = *Shipboard Rolling Vertical Landing*
STOVL = *Short Takeoff and Vertical Landing*
UFCD = *Up Front Control & Display*
UK = *United Kingdom*
VAAC = *Vector-thrust Aircraft for Advanced Control*

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I. Introduction

Since the beginnings of Naval Aviation with Eugene Ely's landing aboard the USS Pennsylvania just over a century ago, very little has changed with respect to how the pilot manipulates the cockpit controls to fly at the lowest practical approach speed by principally managing glideslope with throttle, angle of attack with pitch stick inputs, and line-up with lateral stick. These inputs are tightly coupled such that any change in one parameter will have an adverse impact in the other controlled parameters. In order for the pilot to land at the desired touchdown point, a significant amount of practice is required for the pilot to learn how to compensate for the cross coupled nature of the underlying aircraft flight characteristics. This is accomplished by numerous field carrier landing approaches (FCLP) under the supervision of the experienced Landing Signal Officer (LSO). Once the pilot has demonstrated the requisite landing performance can be achieved ashore, the pilot is then required to demonstrate landing performance at the ship to be carrier qualified. Each pilot must complete this shore-based and shipboard performance qualification before any operational deployment workup events. To qualify the entire air wing requires substantial FCLPs and at-sea ship periods for all pilots to demonstrate the minimum acceptable skill level. This workup qualification exercise exacts a substantial toll on the fleet aircraft service life as well as flight hour costs expended. A recent Office of Naval Research study, Ref (1), showed that the US Navy spends over ~~a~~ $1-billion dollars annually to train pilots in FCLPs and Carrier Qualification (CQ) for six deployed carrier groups annually while only accounting for the flight hour costs combined with a monetized aircraft service life expended.

The US Navy led a joint flight research program with the United Kingdom Ministry of Defence (MoD) with the goal of reducing the workload and training burden for future Short Takeoff and Vertical Landing (STOVL) aircraft. This program used a unique, UK developed, fly-by-wire Vector-thrust Aircraft for Advanced Control (VAAC) Harrier aircraft. This aircraft allowed the engineers to program the flight control software in a rapid development environment where changes could be made overnight and uploaded to the aircraft. This was achieved because the mechanical flight controls were back-driven by servo commands from the Flight Control Computer under the monitoring of the safety pilot who could disconnect the system if any flight safety concern emerged during test. Under this effort, a wide range of flight control concepts were investigated and mapped to various cockpit control inceptors.

What emerged from this research was a radical control concept called Unified STOVL Control in which longitudinal stick commanded flight path, the left hand inceptor (i.e. throttle) commanded acceleration and lateral stick commanded bank angle. These axes were also decoupled such that if the flight path was set, the pilot could accelerate and decelerate along that axis without impacting flight path. All of the commands were managed by the full authority FCS. The pilot simply maintained a front side approach control strategy during the approach to hover, i.e. longitudinal stick resulted in increasing or decreasing flight path, throttle commanded acceleration / deceleration or in a center detent held speed. Gone from this concept was manual manipulation of engine power, nozzle lever angle, and pitch attitude. All of that was managed by the FCS giving the pilot direct command of flight path angle and speed. The successful completion of this research program resulted in this highly augmented control being the preferred control solution for the F-35B STOVL aircraft. The detailed results of the VAAC program were previously reported in Ref (2). This highly augmented concept of control gave the pilot direct command of flight path, speed and bank angle while providing the necessary axis decoupling required. The F-35B completed its initial Development Testing in October of 2011 aboard the USS Wasp. The results confirmed the ease and intuitive control strategy originally developed under the VAAC program.

Based on the success of this program, the US Navy turned to the next most difficult aviation task which was the fixed wing carrier landing task. The same principles applied in the VAAC program were proposed to simplify carrier landings by providing direct command of flight path and line-up which were decoupled from one another while the flight control system managed on-speed approach angle of attack. Similar ideas were considered by the US Navy in the mid 1970's and 80's, Ref (3 & 4). The ONR provided initial seed funding of ~$200,000 for NAVAIR to demonstrate the potential of this type of control concept for carrier landings under the project name MAGIC CARPET. The initial research results showed substantial promise to eliminate the majority of the pilot workload in performing a carrier landing. So positive was the response that additional research funding was provided to mature both the control laws as well as the head up displays. The success of this research effort was demonstrated to the Naval Aviation Enterprise (NAE) Leadership who saw this capability as a revolutionary change on how we conduct fleet operations today. Based on the research success, the Chief of Naval Air Forces, (CNAF) requested the F/A-18E/F program office to sponsor a low cost demonstration of this control law capability in the Super Hornet at sea. US Navy engineers met with Boeing and provided the detailed design changes required to meet this demonstration goal. The remainder of this paper will discuss the control strategy along with the test results accomplished aboard the USS Bush in April 20-22, 2015.

II. DESCRIPTION OF FLIGHT CONTROL MODES

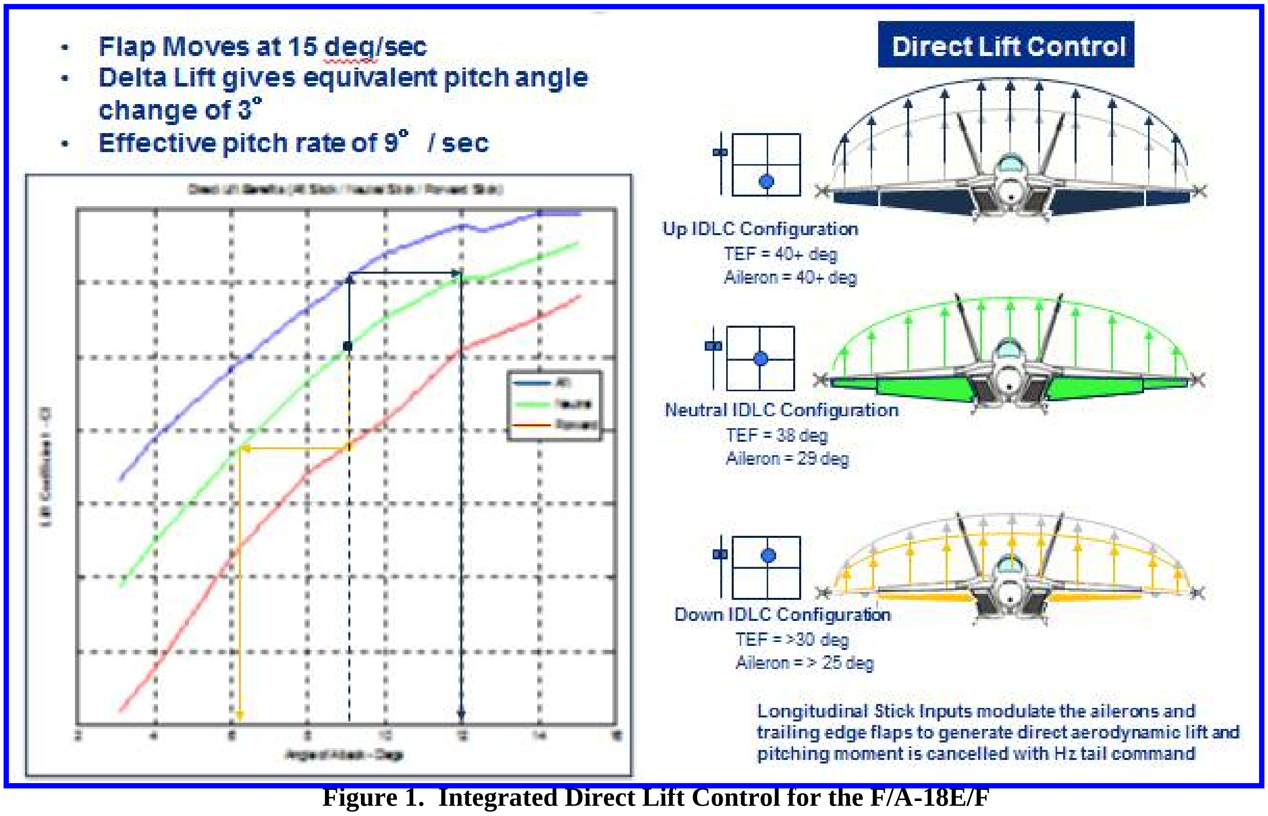
The flight control strategy in the MAGIC CARPET project follows the prescription from the VAAC program in that the pilot is provided direct command of the parameter that the pilot is trying to regulate during the carrier approach which is flight path. The pilot pitch stick commands a change in flight path and the flight control system then manages the control surfaces in combination with sensor feedbacks to close the loop around flight path. This is in contrast to current and legacy carrier control concepts in which the pilot manipulated lower level raw effectors of flight path which are engine thrust via throttle commands and horizontal tail inputs to command pitch attitude to achieve desired flight path and angle of attack. These two parameters are tightly coupled such that any change in one parameter directly and adversely impacts the other parameter. The control strategy employed in this research eliminates this coupled interaction and allows changes in flight path without impact to approach angle of attack. Similarly, bank angle changes do not result in a significant change in either flight path or angle of attack. This decoupled response is an enhancement to the approach task by removing the requirement for the pilot to learn the compensation required to minimize cross axis coupling. Learning this compensation skill is achieved today with repetitive training via FCLPs. The underlying foundation that also enhances flight path command bandwidth employs Integrated Direct Lift Control (IDLC) in response to the pilot pitch stick inputs.

A. Integrated Direct Lift Control

The US Navy first explored the benefits of direct lift control as far back as 1965 on a demonstration effort where this was implemented on an F-8 Crusader which landed aboard the USS America, Ref (5). The direct lift compensation was commanded by a pilot actuated, stick mounted thumbwheel which commanded proportional deflection (up / down) of the wing trailing edge surfaces to increase or decrease the wing camber and lift respectively. Test pilot comments indicated that this change made a profound impact on the precision of flight path control with direct lift inputs. The results of the F-8 demonstration program then formed the baseline design for DLC that was employed into the F-14A Tomcat during its design and development using upper wing surface mounted spoilers to modulate lift. For nearly 30 years, F-14 Tomcat pilots understood the benefits of DLC during carrier landings, however this benefit came at the expense of an additional cockpit inceptor, the stick mounted thumbwheel. Therefore, the pilot controlled flight path with stick, throttle, and now DLC thumbwheel actuations. All of these inputs also affect angle of attack, so while flight path performance improved; it came at the expense of additional workload by adding yet another cockpit command inceptor.

As a part of the Joint Strike Fighter program concept demonstration phase, Lockheed Martin proposed and demonstrated the benefits of an Integrated Direct Lift Command (IDLC) on the X-35C aircraft. Gone was the control stick mounted thumbwheel, and now the trailing edge flaps and ailerons were commanded by the Flight Control Computer (FCC) in response to the pilot's throttle for manual control of thrust or as a function of pitch stick inputs during auto throttle approach modes. X-35C shore-based flight testing confirmed the benefits of integrating this into the underlying control strategy without needing an additional cockpit inceptor. The X-35C variant showed good glideslope control with both manual throttle control as well as approach to landings with auto throttle mode engaged as discussed in Ref (6). This design formed the basis of the current production control concept that was implemented in the F-35C.

The IDLC concept developed for the F-35C was reviewed for benefits to the F/A-18E/F Super Hornet aircraft. The Super Hornet uses more efficient slotted flaps and ailerons to produce high lift for the approach and landing vice the plain flaps on the F-35C. Initial off-line analysis and simulation studies in this research showed that the aircraft had excellent potential for implementing IDLC for carrier approach generated +/- 0.1g delta normal acceleration for the deflections studied. An optimization effort was conducted which showed that by raising the trailing edge flaps and ailerons from their 40 degree fixed full flap position to 38 degrees and 29 degrees, respectively, provided the level of delta g capability while only impacting approach speed by a 4-5 knot increase. The design goal was to maintain the current approach speed with flaps deflected at 40-degrees for the IDLC flap and aileron trim position. This was to avoid a penalty to increased landing loads and/or required wind over deck requirements. Based on ref (7), the US Navy conducted and published a study that showed the original vision over-the-nose requirement that set the Super Hornet approach AOA at 8.1 degrees could be relaxed by a degree without any significant impact to vision over-the-nose based on current landing concept of operations. Therefore, for this flight demonstration effort, all of the testing was conducted at 9.1 degrees AOA in order to provide IDLC capability with no penalty on increased approach airspeed. The benefits of IDLC in the Super Hornet are shown in, figure (1), where the aircraft achieves a delta lift with flap and aileron deflections which is the equivalent to an increase or decrease in lift with a change in AOA by 3 degrees. In contrast, the IDLC lift change occurs at the rate limit of the trailing edge surfaces within 0.3 seconds which is much faster than the ability to change AOA with the existing aircraft pitch attitude bandwidth.



- Flap Moves at 15 deg/sec
- Delta Lift gives equivalent pitch angle change of 3°
- Effective pitch rate of 9° / sec

Longitudinal Stick Inputs modulate the ailerons and trailing edge flaps to generate direct aerodynamic lift and pitching moment is cancelled with Hz tail command

Figure 1. Integrated Direct Lift Control for the F/A-18E/F

B. Flight Path Rate Command

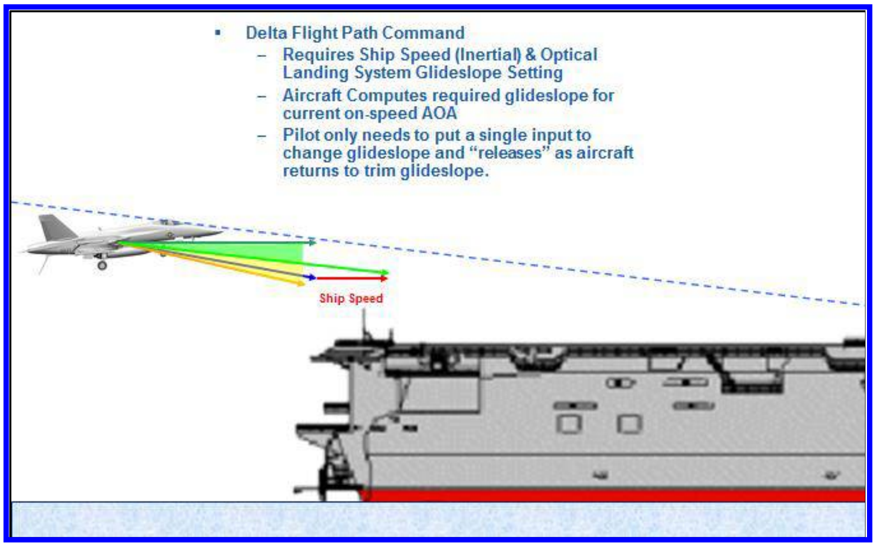
Flight path rate command is the initial augmented flight control mode that is engaged once flaps down have been selected. This mode closes the control loop around an Inertial Navigation System (INS) calculated flight path angle. The current Super Hornet already has this mode as an outer loop control mode called Flight Path Angle Hold (FPAH). The MAGIC CARPET control concept adds IDLC in combination with FPAH control mode which greatly enhances the flight path response bandwidth with pilot longitudinal stick inputs over the current design. The engagement of this mode is accomplished by selection of the existing FPAH push tile on the Up Front Control Display (UFCD) panel with a subsequent depression of the stick mounted Nose Wheel Steering (NWS) engage button. A flight test Dial-A-Function (DAF) capability also allows the depression of the NWS engage button to enter the mode directly without the need to use the UFCD.

This control mode also implements a pitch rate response in combination with IDLC resulting in the flight path time constant lag T-theta-2 equal to zero. This effectively holds the approach angle of attack reference constant for pitch stick inputs such that pitch attitude and flight path change at the same rate with no lag. This effectively limits the pitch rate response such that there is no additional pitch rate for increased stick deflections greater than ~1" of stick deflection. This was tested in the research simulation and showed that all practical nominal and off- nominal approach conditions were adequate to make a required flight path correction in a timely manner. In order to address an extreme condition in which the pilot would need an increased pitch response, the control law adds proportional horizontal tail with increasing stick deflection greater than +/- 2 inches. This allows additional pitch rate response at the expense of maintaining on-speed angle of attack. This design resulted in an effective constant pitch rate and flight path rate response deadband from ~1" to 2" deflection. There were no perceived negative impacts to this design from the initial simulation testing completed, so this design was implemented for the initial demonstration program.

The flight path rate command mode is useful in setting any desired flight path angle by commanding a rate of change of flight path with stick deflections and when the stick is return to center, that flight path angle is held constant. This is a lower pilot workload control mode than the current Automatic Throttle Command (ATC) mode owing to IDLC and closing the loop around flight path. The flight path rate control mode would be used to fly the level downwind leg and the descending turn to the final approach to landing. This is a lower workload method of control for the final approach to landing and was tested to show those benefits. The workload during the final approach phase requires two pilot stick inputs to correct an error in observed glideslope, an initial stick input to increase or decrease the flight path to correct observed errors in the desired flight path and a subsequent input to recapture the glideslope that keeps the desired glideslope constant. While this is a lower workload control mode than legacy ATC or manual throttle control modes, there is yet a lower workload control mode for making precision path changes during the final approach. This subsequent control mode will be discussed in the following section.

C. Delta Flight Path Command

The Delta Flight Path Command mode results in the flight control system calculating a reference flight path at center stick deflection that is a combination of the Improved Fresnel Lens Optical Landing System (IFLOLS) glideslope setting in combination with a pilot entered ship speed. This reference flight path is shown in figure (2) by the green flight path angle vector. As the ship speed increases, the reference flight path decreases so that the pilot's eye remains on the fixed IFLOLS glideslope setting, typically 3.5 degrees which is moving with the ship.



- Delta Flight Path Command
  - Requires Ship Speed (Inertial) & Optical Landing System Glideslope Setting
  - Aircraft Computes required glideslope for current on-speed AOA
  - Pilot only needs to put a single input to change glideslope and "releases" as aircraft returns to trim glideslope.

Figure 2. Delta Flight Path Command Mode

The pilot engages Delta Path (DP) mode when the aircraft is at or near the desired glideslope as observed with the IFLOLS "meatball" or "ball" being near center of the reference datum lights. In DP mode the pilot simply observes errors in the IFLOLS meatball and inputs a steady stick deflection to command a proportional delta flight path steeper or shallower than the computed reference as shown. This constant longitudinal stick deflection is maintained until the meatball is approaching the center and with a little anticipation, the stick input is released to the center detent and the FCC commands the aircraft back to the desired reference based on ship speed. This removes the additional pilot workload that is present in flight path rate command where the pilot has to manually capture and maintain the aircraft flight path back to the reference flight path after each flight path correction. In DP mode, the pilot simply releases the longitudinal stick input without having to spend the time needed to return the aircraft to the reference. For example, if the pilot observes that the ball is above the reference datum lights, a constant forward stick input results in a steeper delta flight path command which moves the ball down towards the reference datum such that the rate of change in the ball is directly proportional to the stick deflection. The greater the error, the larger the stick input required to quickly capture the centered or desired glideslope. This is a very intuitive and linear response to correct observed errors without the need to determine how much engine thrust reduction (increase) and pitch attitude change is required to achieve the same balanced and steady correction in the current manual control method.

Additionally, not having the added task of returning the aircraft to the desired flight path manually, as is required in FPAH mode, this provides additional spare capacity for the pilot to move their attention to line up corrections sooner. DP mode also allows significant bank angle changes required for line up corrections without adversely impacting the commanded flight path and a centered ball condition. This decoupling between the flight path and lineup also results in improved lineup performance even though the lateral axis control laws were not changed, owing the improvement directly to the increased capacity for the pilot to observe lateral errors and make these corrections.

D. Head-Up Display Symbology

The joint US-UK VAAC research program also established a fundamental and underlying principle that flight control improvements must be accompanied by pilot Head-UP Display (HUD) and heads down displays that are task tailored to the engaged mode of control. The displays should provide the pilot with cues that indicate both the error in the desired control parameter, the commanded change to address the error and mode engagement status. The task tailored displays then provide the pilot with the added situational awareness that allow expeditious, accurate and repeatable corrections in both glideslope and line-up. The display is intuitive and consistent with the control mode that is engaged. Much of these concepts have been researched by both NASA in Ref (8), and the VAAC program in reference (9). The VAAC program researched ship relative display symbology as a part of a strategy to provide the pilot with HUD displays that allowed accurate touchdown dispersion such that the Royal Navy could establish a Shipboard Rolling Vertical Landing (SRVL) capability which allows improved weapons and fuel bring back weight over a vertical landing. Because the aircraft is landing on the Queen Elizabeth Class carrier with approximately 35 knots of relative ground speed and braking to a stop on the deck, accurate touchdown is fundamental to the successful execution of the SRVL. The outcome of this research was a set of shipboard HUD display improvements that are ship-relative or compensated for ship speed. This is similar to the ship-relative displays that are used in the marine variant of the Rafale M aircraft. The accurate touchdown performance for the SRVL is nearly identical to the conventional carrier landing task but separated by about 80 knots of relative approach speed difference. So, the US Navy has worked in concert with the MoD to enhance and improve both ship relative HUD concepts along with new deck mounted optical landing systems discussed in reference (9).

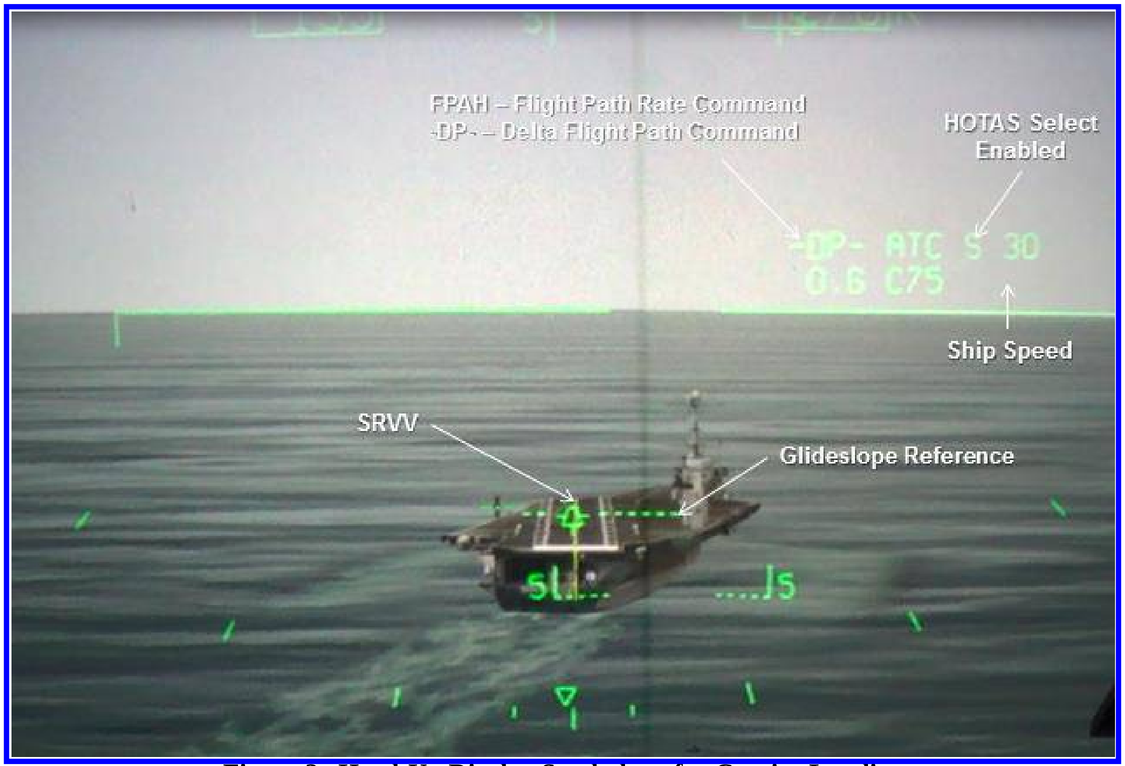


Figure 3. Head-Up Display Symbology for Carrier Landing

The results of the SRVL efforts were expanded under the MAGIC CARPET research effort with the focus on the carrier landing task. The design principles were to provide the pilot with HUD display symbology that gave improved observations of glideslope error, line-up error, command magnitudes and specific modal awareness as to which control law mode was engaged. In addition, the pilot was provided with both Hands-On-Throttle-And-Stick (HOTAS) commands as well as information on the heads down multifunction displays.

Figure (3) highlights the significant additions to the landing display symbology that accomplishes the above situational awareness. The most significant of these new symbols is the Glide Slope Reference Line (GSRL) which is similar to what was incorporated in the F-14D HUD. The GSRL is a fixed dashed line in the pitch ladder at the location where the desired glideslope set by the IFLOLS landing system. This is typically 3.5 degrees for a majority of carrier landings and only goes up to 4.0 degrees for high natural wind over deck recovery operations. The relative geometry works out such that if the pilot moves the GSRL forward or back with reference to where the IFLOLS datum lights are located on the deck will result in the aircraft being very close to the desired glideslope and a centered ball position. This relationship allows the pilot to quickly see deviations and correct them at the beginning of the approach to the carrier. The next and equally important symbol is the Ship Relative Velocity Vector (SRVV). When the SRVV is aligned with the GSRL, then the aircraft is paralleling or on the desired glideslope. For example, if the GSRL is located forward of the point where the IFLOLS datum lights are located, the aircraft is high or above the desired glideslope angle. The pilot simply then moves the GSRL line aft on the deck, by moving the SRVV below the GSRL, thus steeping the flight path which will result in the GSRL moving aft towards the datum deck location and as the GSRL aligns with the datum (and IFLOLS ball is centered), then the pilot repositions the SRVV on the GSRL and the aircraft should remain close to the desired glideslope. In Delta Path control mode, the above example the pilot simply pushes and holds forward stick which results in the SRVV moving down or a steepening flight path and as the GSRL aligns with the datum the pilot simply releases the stick input and the SRVV is commanded back to the GSRL reference. The larger the deflection of the SRVV from the GSRL, the faster the glideslope correction will occur. This provides the pilot with complete situational awareness of the glideslope error and how fast or the rate of change in glideslope is required to capture the desired centered ball glideslope quickly. The HUD also provides tag lines that indicates to the pilot which control mode is engaged, if the auto throttle is engaged and ship reference speed being used to calculate the ship relative HUD symbology references.

III. Demonstration Test Method

This initial flight test on the F/A-18E/F Super Hornet was designed to be a limited, low cost demonstration program to prove that the performance results that were being demonstrated in the F/A-18E/F/G engineering simulation located at Naval Air Systems Command (NAVAIR) Patuxent River, Maryland, would indeed be realized under actual carrier landing operations. The F/A-18 Program Office contracted with the Boeing Company and work began in January of 2014. NAVAIR engineers began by laying out the required changes to the Super Hornet control laws and worked closely with Boeing control law team to implement these changes into the operational flight program. The changes to the production control laws were enabled by a flight test Dial-a-Function (DAF) capability which allows the team to tune the control system gains during early flight tests. The testing was focused on three configurations, 1) Clean aircraft with single centerline fuel tank, 2) Maximum Lateral Asymmetry Store Loading and 3) five external fuel tank configurations so that the demonstration could span the critical store loadings. The combined NAVAIR and Boeing team completed the necessary control law changes, formal software integration testing and hardware in-the-loop testing. A flight clearance for these configurations was issued in late November 2014.

In addition to the development efforts of control modes for the Super Hornet, the NAVAIR team also met with flight control engineers and program leadership on the F-35 Joint Strike Fighter program. In these meetings, NAVAIR showed the landing dispersion performance improvements that were being accomplished in the F/A-18 simulation testing and how, with some very minimal changes in the F-35C control laws, beneficial improvements in landing dispersions with reduced pilot workload could also be achieved. Lockheed leadership saw the benefits that Delta Flight Path control could provide to the F-35C, with knowledge that the existing F-35C control laws already incorporated IDLC with Approach Power Compensator control mode. It was a minor addition to the existing control laws to add the Delta Flight Path command mode to the F-35C aircraft. That decision was adopted and development efforts on the F-35C were initiated in parallel with the existing development efforts on the F/A-18E/F.

A. Shore Based Flight Test

The NAVAIR Test Plan for the F/A-18E/F was signed on January 15, 2015. The initial flight test build-up for the shipboard trial was focused on the clean plus centerline external store configuration, so that the team could answer the question regarding landing performance improvements observed in the simulation in the shortest time possible. The first flight occurred on February 6, 2015 flown by LCDR Tyler Hurst and Mr. Michael Wallace (Boeing Test Pilot) in which initial mode engagement occurred at altitude (3000-5000 feet) for gain tuning of the IDLC and both flight path rate and delta flight path command modes. Once the joint Navy / Boeing team were satisfied with the performance up and away, the aircraft returned to the field for a series of nominal approaches in Delta Path command mode. The early indications from first flight were that we were achieving the performance observed in the simulation. The second flight was flown by project lead test pilot, LT Brent Robinson, who expanded the envelope from nominal to off nominal approach conditions. Initial pilot feedback from these initial flights were an unqualified success in demonstrating the low workload and precise control were being achieved for both nominal and off-nominal approach conditions.

The shore based flight testing continued with two test aircraft and was expanded to include a total of 5 test pilots flying both flight path rate and delta path command modes. The focus was on clearing the centerline loading in preparation for the shipboard demonstration. The shore based testing, as well as required FCLP qualifications, concluded on March 23, 2015 with a total of 71 approaches flown in Delta Path and 50 approaches in Flight Path Rate command modes for both nominal and off nominal conditions. The two flight test aircraft were cleared for shipboard operations based on the confidence and performance that was achieved during the field tests.

B. Shipboard Flight Test

Shipboard testing commenced on April 20 and completed on April 22, 2015. Over this test period, the test team flew 5 pilots in two test airplanes accomplishing 199 deck landings to include initial carrier qualification requirements in current manual throttle control. The team achieved a total of 181 landings in the augmented modes with 117 landings conducted in Delta Path Command and 64 landings in Flight Path Rate command. These landings were accomplished with both nominal and off-nominal errors in glideslope and line-up conditions shown in Fig (4). The off-nominal test cases were set up to determine if cross axis control inputs could be achieved in both Flight Path Rate and Delta Path with the latter being the focus since the pilot had to hold constant longitudinal stick inputs to make glideslope corrections while simultaneously making lateral stick inputs for line-up corrections. The other challenge to landing on the carrier is the external effects related to wind over deck and the induced carrier air wake characteristics. At high winds, there is a downwash aft of the stern of the ship that results in aircraft settle near the ramp as well as a loss of 8-10 knots of wind over deck with starboard winds due to the blanking of the wind by the island superstructure. All of the tested wind cells are shown in figure (5) and are designed to determine how well the augmented control systems coped with the external ship air wake disturbances.

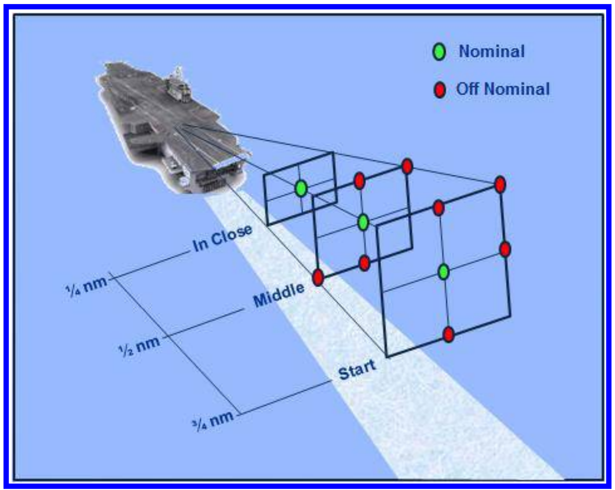


Figure 4. Nominal and Off-Nominal Conditions

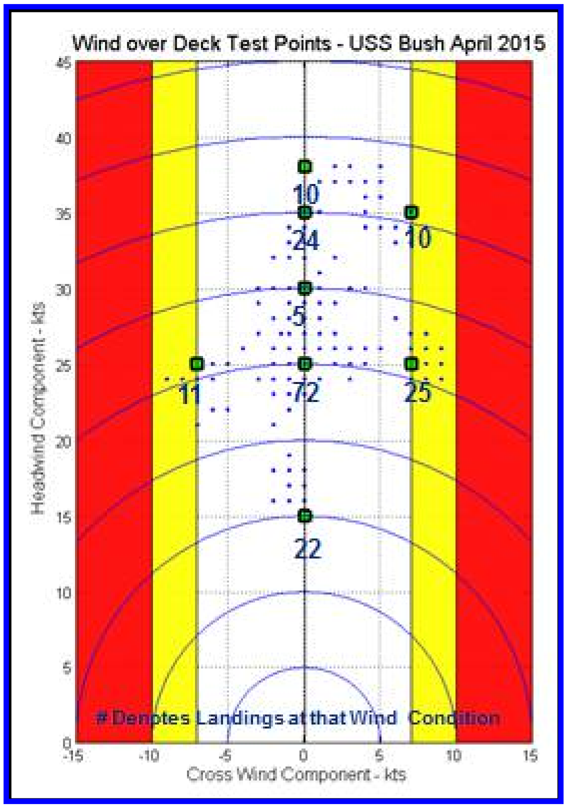


Figure 5. Wind Over Deck Test

IV. Shipboard Results and Discussion

A. Handling Qualities Discussion and Pilot Comments

One of the key performance metrics in this development effort was that we were lowering the pilot workload and increasing his excess spare capacity during the approach and landing. The control concept must deliver a simple and intuitive method for the pilot to recover the aircraft aboard the aircraft carrier which is easy to learn. This would, for the first time in 50 years, allow the Navy to potentially reduce the number of FCLP landings required by the pilot to achieve the demonstrated performance required to carrier qualify and that would directly result in substantial reductions in training and proficiency operational costs. An exhaustive simulation study was conducted in 2012 and the overall pilot opinion showed an average of two (2) Handling Qualities Rating (HQR) points improvement over the normal Manual (M) stick and throttle, Auto Throttle (AT) and the advanced Delta Flight Path mode (FP). The HRQ summary data are presented in Fig (5).

The assignment of HQRs was consistent with the HQRs achieved at the USS Bush shipboard trial. The qualitative assessment of the lower pilot workload while achieving the desired task performance can also be observed from the pilot stick inputs. Figure 6 is a set of four time histories that are a function of increasing augmentation from columns 1 to 4. The x-axis is time to touchdown on the ship which represents the pilot's workload from the start of the approach to touchdown. The first column is the pilots stick and throttle inputs required during a manual approach to landing. The longitudinal stick inputs can be characterized as continuous, high frequency and

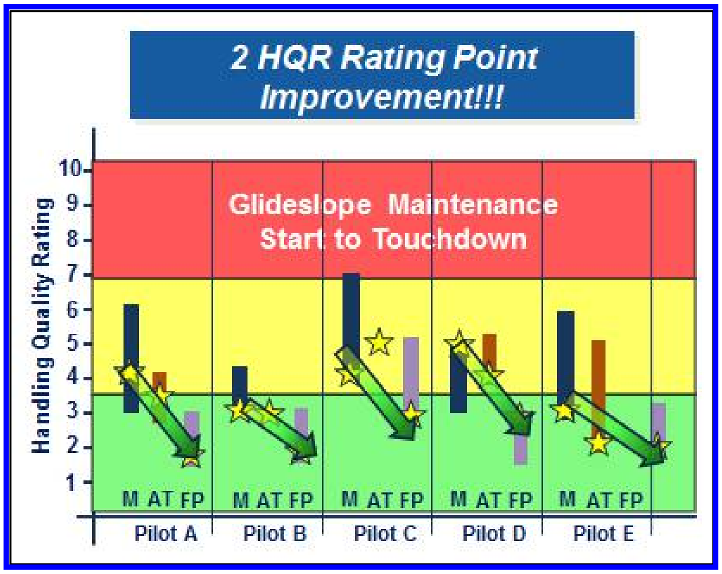


Figure 5. Handling Qualities Summary Simulation Evaluation

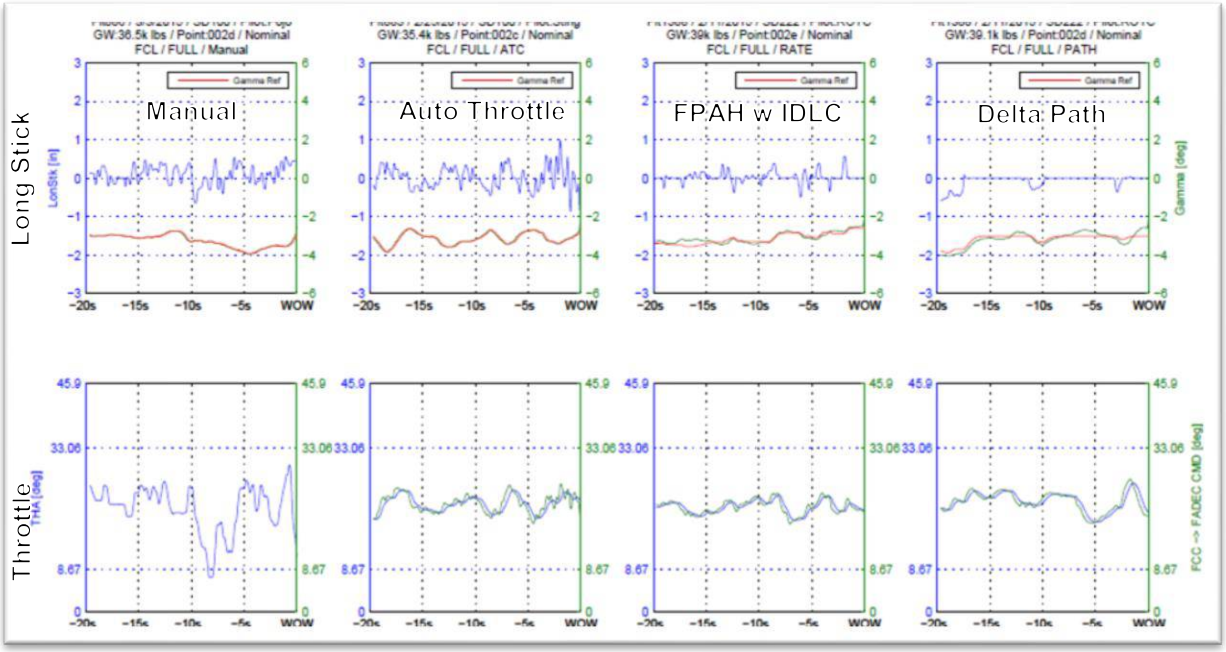


Figure 7. Approach Longitudinal Stick and Throttle Inputs versus Increasing Control Augmentation

magnitude to achieve the desire performance. The second column is with the current Auto Throttle mode engaged where the pilot no longer has to manage both stick and throttle inputs. While the workload for throttle input has been managed by the FCC, the pilot is still responsible to fly the desired flight path with the longitudinal stick. It is clear in the Auto Throttle mode that the pilot is still required to make continuous high frequency and magnitude inputs similar to the manual approach. The third column represents the approach in FPAH with IDLC augmented mode engaged. It is clear from the plot that longitudinal stick inputs have dropped in both magnitude and frequency content to achieve the desired performance when compared to the two previous approach control modes. The fourth column represents the precision approach mode, Delta Path. It is very clear that the pilot inputs and workload have demonstratively reduced to minor flight path corrections as the aircraft nears the carrier landing. This is due to the aircraft FCC managing and closing the loop on the desired flight path so long as the pilot continues to correct for observed bias (high / low) as observed from IFLOLS and line up errors. It is clear from this level of reduction in the pilot workload in this plot, as well as all landings in Delta Path, that the pilots had additional spare capacity to refine observed lineup errors which were measured in the overall landing dispersions results.

The overall summary of the pilot comments from the shipboard trial were very favorable and reflected the observed reductions in workload from the above plots. The pilots used words such as “a game changer,” “fantastic,” and “awesome” to describe the ability to make large off-nominal corrections easily and with excellent precision in both glideslope and line up capture and maintenance. The pilots commented that it was easy to capture and maintain glideslope within ½ to 1 IFLOLS ball at the center reference datum. Also, they commented on the stability of the glideslope during the approach in that the IFLOLS meatball stayed where you left it even with moderate bank angle changes when making lineup corrections. The flight controls also did a very good job minimizing the glideslope errors created by external ship air wake and burble disturbances. The pilots commented that they could easily make one or two last minute glideslope corrections even after crossing the ramp. This level of performance with low pilot workload just simply cannot be accomplished with current manual throttle and stick commands and exemplifies the positive benefit of direct lift in combination with these highly augmented modes.

All pilots preferred the advanced HUD displays as it provided excellent situational awareness on the control mode that was engaged. The shipboard relative velocity vector in combination with the glideslope reference line also provided the pilots with another tool to determine both glideslope and lineup errors and the required command inputs to minimize the errors and quickly recapture the desired glideslope and line up during the approach.

The pilots did report on some minor deficiencies that did not impact landing performance but should be considered for improvements in future control law updates. The longitudinal stick to IDLC flap command gradient was steeper than optimum and resulted in some minor surging in axial acceleration with flap deflections. Pilots only commented on this when doing more clinical step inputs on longitudinal stick during gain tuning, however it was not generally observed or reported when flying actual approaches to the ship. This sensitivity was particularly evident in half flaps where the approach speed was higher and available IDLC flap command was double that in full flaps configuration. This required the pilot to adjust their compensation in half flaps to not overdrive flight path corrections. Adjusting their compensation in half flaps resulted in the same excellent touchdown performance as compared to the full flaps landings. For this flight test effort, there were no DAF gains available that could adjust this sensitivity during the flight test program, however, subsequent adjustments have been completed that improve and eliminate this sensitivity and demonstrated in the simulator.

B. Touchdown Dispersion Analysis

The final objective of this demonstration test was to determine if the landing touchdown dispersions would be as good as predicted from the 2012 simulation trial. The test team utilized high speed photogrammetric techniques to capture the hook touchdown location for all of the shipboard approaches. This included the initial carrier qualification (CQ) landings flown in current manual stick and throttle inputs for all five test pilots. In addition to these manual landings, fleet squadrons were aboard to complete their carrier qualification requirements in advance of workups for operational deployments. Their touchdown dispersion performance was also measured and included in the statistical summary of for both manual throttle and auto throttle landing modes. This gave a good comparison between the current manual controlled landing modes and the augmented control modes under test.

The touchdown dispersion data was recorded for all nominal and off-nominal matrix of start conditions as well as all low, high and crosswind conditions. It was hard to distinguish any significant touchdown dispersion sensitivity to these off-nominal conditions, so the combined results of all nominal and off nominal landings are shown in Fig (8). This figure shows the hook touchdown points as they relate to the desired hook touchdown point located between the #1 and #2 arresting gear wire. The USS Bush is a 3 arresting wire ship where all previous Nimitz class ships utilize 4-wires. The relative location of the actual #1 wire on the 4-wire ship is depicted by the dashed line. The results for the precision path control achieve in Delta Path are shown by the green data points in the plot. Flight Path Angle Hold points are shown in blue with the overall CQ manual landings shown by the red data points. Delta Path control resulted in outstanding landing performance with the mean touchdown of 0.4’ forward of the ideal touchdown and the 1-sigma value of +/- 18.2’. This performance represents a reduction by over 50% in touchdown dispersion when compared to the current manual landing method shown by the CQ points in red. This substantial improvement in landing performance is achieved with much lower pilot workload owing to the benefits of closing the loop around flight path in combination with IDLC. This augmented control improves the flight path response bandwidth performance and when combined with an easy and intuitive cockpit control interface and HUD displays has demonstrated a dramatic improvement in landing performance. This level of touchdown dispersion performance will lead to improvements in fleet boarding rate as well as safety.

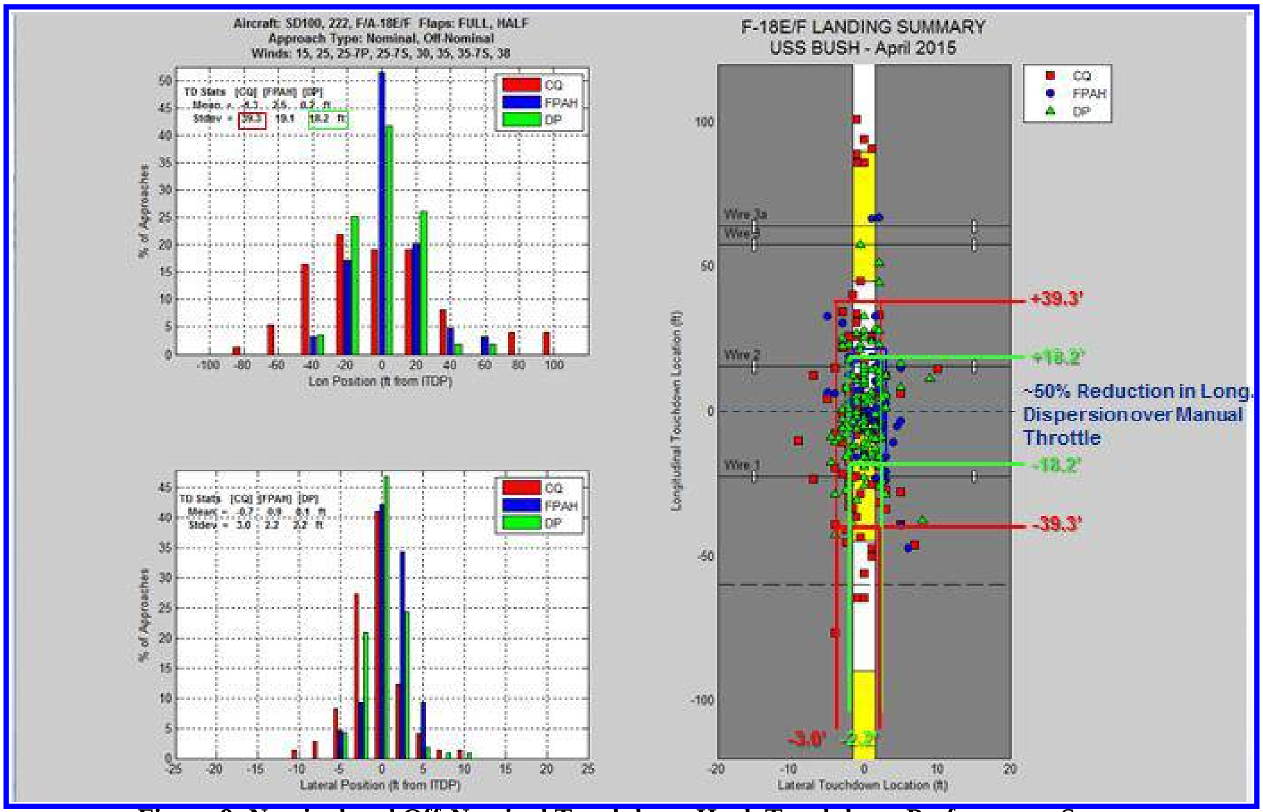


Figure 8: Nominal and Off-Nominal Touchdown Hook Touchdown Performance Summary

As previously discussed, Lockheed Martin engineering also adopted the Delta Flight Path control mode after observing the landing performance improvements at low pilot workload. The engineering team worked in parallel with the on-going efforts on the F/A-18E/F. The F-35C first tested and demonstrated the benefits of Delta Flight Path control during the first developmental shipboard trial conducted on the USS Nimitz in November of 2014. Figure 9 shows the comparison between the results obtained on the F/A-18E/F and the F-35C.

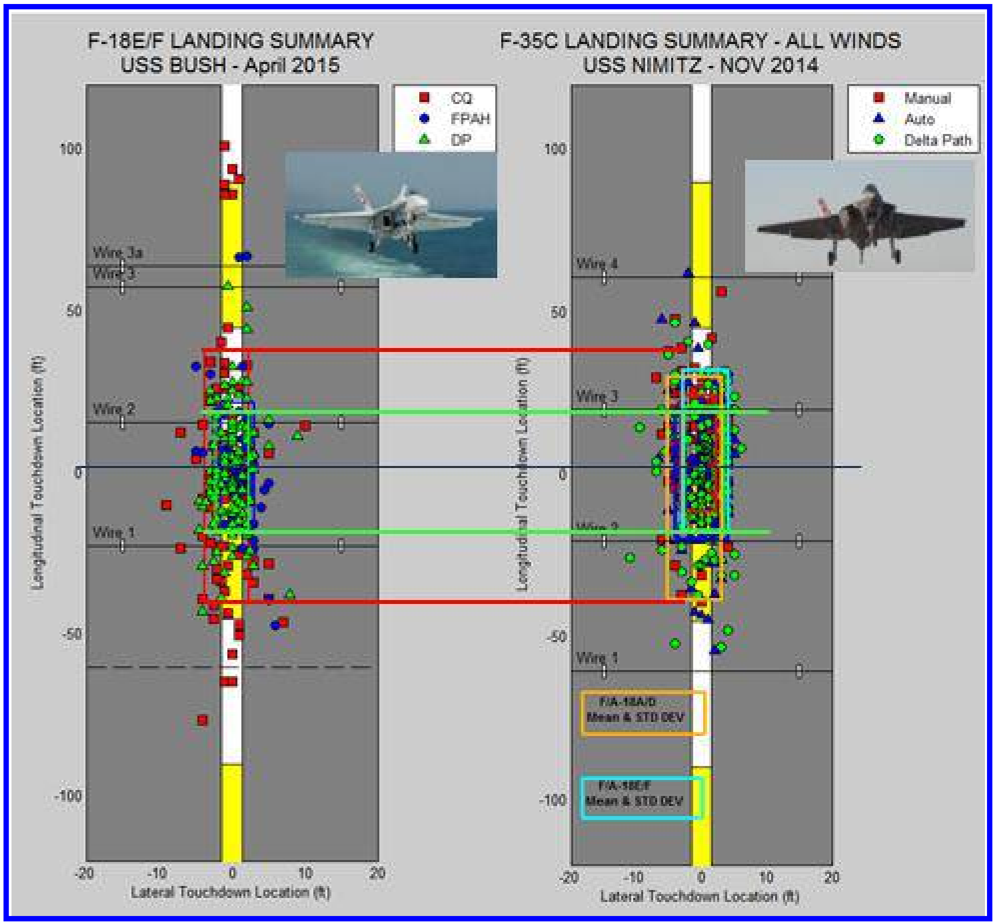


Figure 9: Comparison of the F/A-18E/F and F-34C Touchdown Dispersions

Remarkably, the results obtained on the first test with the F-35C are nearly identical to the results obtained 5 months later when the F/A-18E/F débuted its Delta Flight Path control on the USS Bush. In a different ocean, different test pilots, different sea conditions and more importantly a different aircraft; the touchdown dispersions 1-sigma in Delta Flight Path for the F/A-18E/F was +/- 18.2 feet and the F-35C was +/- 19.1 feet. This comparison clearly demonstrates that it is the underlying augmented control that results in nearly identical landing dispersion performance. This comparison then leads to the beneficial conclusion that the current fleet pilot-to-pilot skill variation in carrier landings from the ab initio pilot to the highly experienced pilot will collapse to a narrow and consistent performance band. Given the simplicity, repeatability and intuitive characteristic of Delta Flight Path command, it also shows promise that there will be little atrophy of the acquired carrier landing skill over time. This may likely allow the Navy to extend the existing carrier qualification currency requirements which will also lower the overall operational costs to the fleet.

C. Touchdown Impact Load Analysis

The largest adverse contribution to the aircraft structure and fatigue results from high vertical velocity impact at deck touchdown. Previous landing surveys conducted by the Navy to determine the statistical distribution of impact loads shows large variations in landing vertical velocity from pilot to pilot. This large distribution results in structural design requirements to accommodate the 3-sigma deviations based on these landing surveys. This drives structural weight to ensure the aircraft will meet its design service life. Early simulations highlighted the benefits of Delta Flight Path control by demonstrating tight consistency in the vertical velocity at touchdown for all landing in various simulated ship deck motion. The underlying construct of Delta Flight Path control allows the pilot to capture and maintain a centered ball early in the approach. Once on or near the desired glideslope, the pilot only is required to make small commanded flight path changes which directly results in small deviations in vertical velocity just prior to touchdown. Figure 10 shows a plot of the pitch attitude versus vertical velocity just prior to deck touchdown.

The red boundary line is the structural design envelope for the F/A-18E/F aircraft. Light blue, yellow and red data points are those points collected in the previous landing surveys conducted on the F/A-18 aircraft. As can be observed, there is a large distribution of both attitude and vertical velocity for the current manual pilot controlled landings from surveys S-67, S-68 and S-71 as compared to the two augmented modes FPAH and DP. Delta Path command mode demonstrates the tightest correlation between the mean and 1-sigma deviations of all of the data. Table 1 shows a summary of the statistical results of the recorded shipboard landings.

The mean pitch attitude for both the FPAH and DP modes was higher by design as the approach angle of attack was raised by one degree to 9.1 degrees to keep the approach speed the same with the IDLC flap bias introduced for both FPAH and DP modes over the current 8.1 degree approach condition. This increase in angle of attack by 1 degree will obviously move the mean pitch attitude from ~5.1 degrees to 6.1 degrees. From Table 1 below, it is clear that Delta Path control results in the tightest deviations in both pitch attitude and vertical velocity at touchdown by over 50% of current landing loads. This reduction in attitude deviations and more importantly vertical velocity variations at touchdown can only have a beneficial improvement in airframe fatigue life.

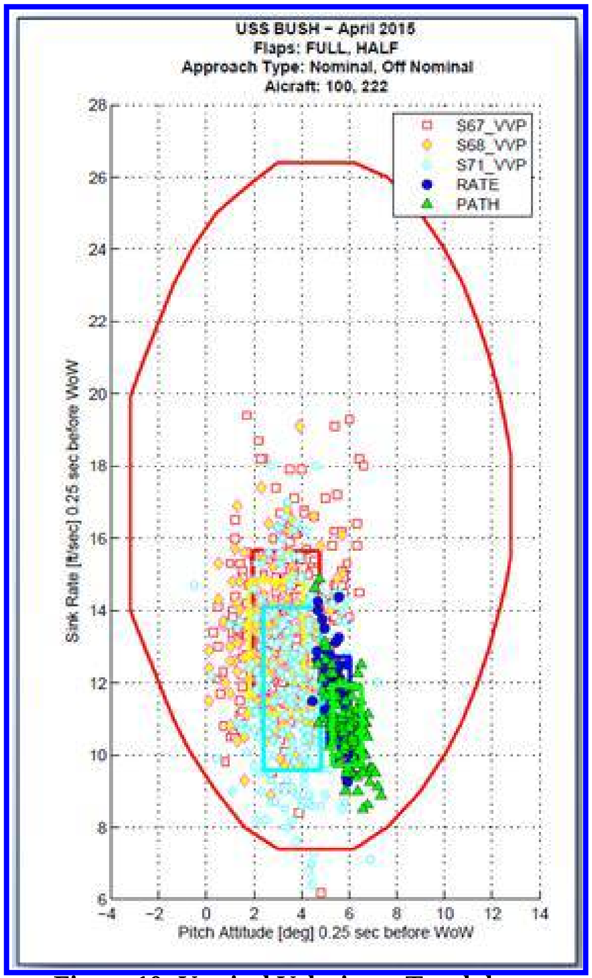
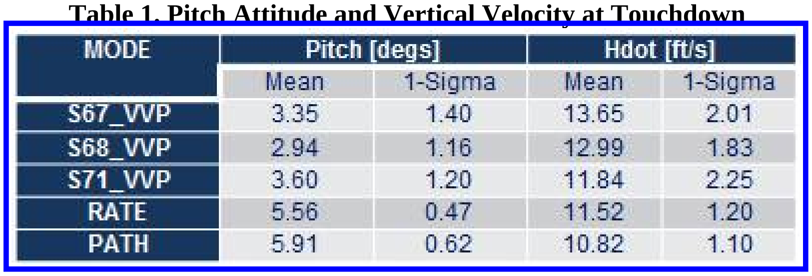


Figure 10: Vertical Velocity at Touchdown

Table 1. Pitch Attitude and Vertical Velocity at Touchdown



MODE	Pitch [degs]		Hdot [ft/s]	
	Mean	1-Sigma	Mean	1-Sigma
S67_VVP	3.35	1.40	13.65	2.01
S68_VVP	2.94	1.16	12.99	1.83
S71_VVP	3.60	1.20	11.84	2.25
RATE	5.56	0.47	11.52	1.20
PATH	5.91	0.62	10.82	1.10

V. Conclusions

This research effort has demonstrated the outstanding benefits that highly augmented control brings to the carrier landing task performance. The Integrated Direct Lift Command when combined with the Delta Flight Path Control allows the pilot to make precise, repeatable and consistent performance when landing on the aircraft carrier. The performance achieved in this testing has shown a 50% reduction in touchdown dispersions which will lead to improvements in the current aircraft boarding rate during deployed operations. Improving the aircraft boarding rate will allow the ship to recover all aircraft in a timely manner reducing the steaming time into wind during the recovery cyclic operations. The intuitive nature of the control concept when combined with the task tailored HUD symbology provide the pilot with an easy method to observe errors in glideslope and line-up which will reduce the time required to become proficient for the ab initio carrier pilot as well as retaining the skill for longer periods between carrier landings. This combination of ease of control and learning will result in a significant reduction in the required training during field carrier landing practice which will have substantial reductions in the cost to train and maintain fleet pilot landing proficiency. The augmented control has also demonstrated a very consistent and tight distribution in vertical velocity at deck impact. This lower mean and 1-sigma deviation in vertical velocity and pitch attitude will have beneficial improvements in aircraft fatigue life impacts which will likely extend available service life.

The US Navy has embraced this control method for both the F/A-18E/F and the F-35C aircraft. In the words of the pilots that flew the augmented modes….”this will be a game changer” to how the Navy conducts deployed operations. This will improve the carrier operational efficiency, performance, and safety when recovering aircraft aboard the carrier. All of this will reduce the cost associated with the carrier landing training expended today and allow the Navy to use these savings for additional mission training proficiency prior to fleet deployment operations. NAVAIR continues to align both the F/A-18E/F and F-35C augmented controls so that both aircraft provide identical controls and displays for fleet deployment. As of this release, the Navy is planning to introduce this augmented control to the fleet beginning in the 4th quarter of 2016 in the F/A-18E/F/G aircraft with the F-35C having this control mode when it achieves its initial operational capability in 2018.

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