Resolving the conflict between ship design and UAV Launch and Recovery deck limits; the development of enhanced dynamic interface study tests

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ABSTRACT

With more than 10 years of MQ-8 Fire Scout Unmanned Air Vehicle (UAV) at-sea deployment on various ship classes, a wealth of ship integration and operations data has been harvested. In general, these various platforms are the results of the Naval Architect’s efforts to design a vessel that performs effectively, safely, and within budget for all communities on-board. However, rarely is there a feedback loop in the design or early acquisition phase offering confident environmental parametric aircraft/ship interface data to the ship deck community users. For the most part, aircraft-deck interface parameters, such as deck motion and air wake field characteristics, are the Navy’s to define. In the case of the UAVs, this defined data is essential for safe and efficient air vehicle launch and recovery events. With mono-hull legacy vessels, certain common seakeeping properties have open ocean performance similarities permitting the test and evaluation engineers to practice standard test procedures with a minimum of modification. For a variety of reasons, this model does not hold with the latest ship acquisitions requiring revisions in testing procedures. Unlike manned flight operations, UAVs require more precise environmental information to make a successful recovery. Enhanced dynamic interface (DI) testing is designed to better understand the effects the new ship classes (i.e. Littoral Combat Ship (LCS)) have on the deck environment. The enhanced study aspects, beyond the standard Naval Air Training and Operating Procedures Standardization (NATOPS) envelope expansion evaluation, are composed of a number of analyses measuring and documenting the responses of the ship to the maritime climate and of the air vehicle in operation, but particularly in recovery mode. Naval Air Systems Command (NAVAIR’s) Program Management Office (PMA 266), Naval Sea Systems Command (NAVSEA’s) Seakeeping and Full Scale Departments have combined with NAVAIR’s Dynamic Interface (AIR 5.1.6.11) and Air Wake (AIR 4.3.2.1) engineering agencies to detail these enhanced at-sea and simulation tests. The article summarizes selected testing and computational methodologies covering ship motions, air wake and their impacts on the air vehicle. The study objectives and performance criteria, providing deck environment definitions directed to the UAV operational algorithms, are discussed and illustrated. Data results are presented as a function of helicopter on-deck stability to encountered deck forces in progressively higher sea conditions.

LIST OF ACRONYMS

AS  Airborne Subsystem  
AV  Air Vehicle  
CFD  Computational Fluid Dynamics  
CONOPS  Concept of Operations  
DI  Dynamic Interface Study  
DIPES  Deck Interface Pilot Effort  
Scale  
EI  Energy Index
FFG  Guided Missile Frigate  
LCS  Littoral Combat Ship  
LPD  Landing Period Designator  
LSO  Landing Signal Officer  
L&R  Launch and Recovery  
MCS  Mission Control Station  
NATO  North Atlantic Treaty Organization  
NOAA  National Oceanic and Atmospheric Administration  
NATOPS  Naval Air Training and Operating Procedures Standardization  
NAVAIR  Naval Air Systems Command  
NAVSEA  Naval Sea Systems Command  
PMA  Program Manager AIR  
PEO  Program Executive Officer  
SHOL  Ship-helicopter operational limit  
UCSD  University of California, San Diego  
UAS  Unmanned Aircraft System  
UAV  Unmanned Aerial Vehicle  
WOD  Wind over Deck

INTRODUCTION

The current US Navy Concept of Operations (CONOPS) for the deployment of the MQ-8 Fire Scout Unmanned Air System (UAS) is to have the system based aboard, amongst other vessels, the Littoral Combat Ships (LCS). Both platforms (UAS and LCS) were developed independently of each other. Since the UAS is primarily operated as a ship-based system, each aircraft system is required to undergo a ship suitability assessment in the form of Dynamic Interface (DI) testing, also known as helicopter-ship qualification analysis, or envelope expansion trials. DI testing evaluates all aspects of shipboard helicopter compatibility including the adequacy, effectiveness, and safety of shipboard aviation support facilities and/or procedures for all ship-based helicopter types. These empirical at-sea interface analyses have been conducted using established protocols for nearly forty (40) years. The ship platforms are designed independently of the air vehicle. Testing in the legacy Navy has occasionally presented the test team with some unique challenges to a legacy platform. With the recent acquisition of new classes of ship platforms, like the LCS, the DI test teams have been confronted by deck responses that are departures from the legacy ships. This article describes some of the trial procedures and solutions developed to improve MQ-8 operations on the Navy’s new platforms.

BACKGROUND

The Navy and Marine Corps Multi-Mission Tactical UAS Program Management Office (PMA-266) of Naval Air Systems Command (NAVAIR) is headquartered at Patuxent River, Maryland, with military and civilian personnel stationed at locations across the United States and around the world.

NAVAIR is organized into eight "competencies" or communities including: program management, contracts, research and engineering, test and evaluation, logistics and industrial operations, corporate operations, comptroller and counsel. It provides support and resources (people, processes, tools, training, mission facilities, and core technologies) to Naval Aviation Program Executive Officers (PEOs) and their assigned program managers, who are responsible for meeting the cost, schedule, and performance requirements of their programs. NAVAIR’s affiliated PEOs are:

- PEO for Tactical Aircraft Programs, PEO (T)
- PEO for Air ASW, Assault and Special Mission Programs, PEO (A)
- PEO for Unmanned Aviation and Strike Weapons, PEO (U&W)
- PEO for Joint Strike Fighter, PEO (JSF)

PMA-266 is part of PEO (U&W). The process of converting a research and development project into an acquisition program of record and then shepherding the program into service typically requires many years. The PMA is responsible not only to track the acquisition program’s performance requirements but to adapt over time the acquisition program with current mission applications and conditions. This certainly includes system growth and technology evolution. One of
the primary responsibilities in PMA-266 portfolio includes the MQ-8 Fire Scout program.

**DYNAMIC INTERFACE**

Dynamic Interface (DI) is defined as the study of the relationships between an air vehicle and a moving platform. It is performed to reduce risks and maximize operational flexibility [1]. Globally, DI is concerned with the effects that one (1) free body has in respect to another free body. Historically, this means the effects that a ship may have on a recovering or launching of air vehicles. However, more recent studies have concluded that the same principles apply to other motion related activities, such as, the boarding of Landing Crafts and/or the Landing Craft Air Cushion (LCAC) vessels into the wells of Amphibious Warfare Ships, the docking of submarines or the launching of unsophisticated missiles.

DI is divided into two broad categories: analytical and at-sea experimental analysis. The analytical provides for a mathematical analysis and solution to flight operations. The methods are not mutually exclusive. Neither method alone can produce a comprehensive and timely solution of the deck interface problem [2].

The traditional approach for DI is the experimental approach; which investigates operational launch and recovery of vehicles, engaging and disengaging of rotors, vertical replenishment and helicopter in-flight refueling envelopes. However, the experimental approach primary focus is on launch and recovery envelope development and expansion. "Shipboard suitability testing" assesses the adequacy, effectiveness, and safety of shipboard aviation. Testing methodologies and procedures have been standardized by such departments at NAVAIR (Patuxent River).

**Dynamic Interface UAV Envelope Expansion**

DI testing of unmanned vehicles is not straightforward. The methodology of replacing piloted evaluations with operator estimates and the corresponding test criteria, is established prior to actual testing. However, it is often found that assumptions applied early in testing may need real-time adjustments to adapt to circumstances found during the test.

Naval air training and operating procedures standardization (NATOPS) or ship-helicopter operational limit (SHOL) limits are determined based on wind and ship motion data as assembled by conducting various launches, approaches, and recovery events. Central in the SHOL determination is the pilot evaluation. The unmanned configuration during testing normally is instrumented to provide, amongst other parameters, oleo compression and deflection, torque monitoring along with indications of precise weight on wheels or skids. The number of landings per condition becomes almost academic since there is no piloted variation or technique since the piloting is the same as originally programmed. The settled approach is to assess system performance using multiple launch and recovery cycles but only one recovery is required to justify an envelope expansion.

Table 1 displays the primary components affecting the DI rating scales. While the other DI functions may be directly or indirectly measured, visual cues assessments are entirely empirical and can be subjective. For UAS evaluations, visual cues are replaced by instrumental analysis [3].

### Table 1 – Dynamic Interface Measures

| o Relative Wind Speed and Direction |
| o Ship Air wake and Turbulence |
| o Ship Motion |
| o Visual Cues or Instrumented (UAS) |

The behavior of an air vehicle to the deck environment of a given ship platform, is the primary objective of the DI envelope expansion tests. In the piloted case, handling qualities, pilot workload, flight control positions and aircraft limitations are used to define the progress of shipboard launch and recovery envelope development (control margins, torque, rotor speed, power margins, excessive pilot workload, inadequate visual cues, inadequate clearance between aircraft and ship structure). Pilots assign ratings
to both the approach and landing, and the takeoff and departure sequences for a specific wind over deck (WOD) condition, in accordance with guidelines set forth in the Deck Interface Pilot Effort Scale (DIPES). Data is evaluated after each flight and plotted on a polar plot. Data points are interpolated to fill in the missing data. The missing data is primarily due to weather conditions which prevents the ship from obtaining the various wind speeds.

If comments and ratings are favorable (DIPES-1, 2, or 3) for both the approach and landing sequence and the takeoff and departure sequence, under a specific WOD speed and direction, the ship will be maneuvered to produce new relative WOD conditions for the next sequence. A sample wind envelope is displayed in figure 1 [4].

Figure 1 – Typical Wind Envelope

A significant portion of the envelope expansion testing procedures centers on aircraft responses to near ship air wake. These are based on assumptions developed over many trials concerning the ship’s responses to the maritime environment. These responses create the deck conditions in which the air vehicle is tested. When these assumptions are shown to be invalid or inaccurate, it becomes necessary to revise the basic testing assumptions. This is exceptionally important when testing and operating unmanned vehicles. In the course of conducting the unmanned sea tests it became evident that greater emphasis is needed on the simulation side to test for contingencies normally diagnosed by a pilot to deal with an unplanned event. In addition, a greater understanding of the control logic is needed representing a pilot decision making process. Several metrics are used to develop the relationship between the simulated and real world.

**REFINING THE DEFINITIONS OF THE UAV x SHIP’S BEHAVIOUR**

As explained earlier, the current CONOPS assigns the MQ-8 to any suitably equipped air capable ship, but designates LCS vessels, in particular. LCS has two variant classes of ships, the Freedom (mono-hull) and Independence (trimaran) class. As part of the Navy deployment process, a ship suitability assessment is conducted in the form of DI testing. DI testing evaluates all aspects of shipboard helicopter suitability and compatibility. A significant component parameter centers on the ship’s motion characteristics, the ship’s control and environmental conditions which control those motions.

In the course of MQ-8B / C and LCS envelope expansion, DI trials were held on both classes of LCS ships, which unexpected ship motions have been measured and recorded. These unexpected motions were almost exclusively observed to be large roll angles. These roll motions may have been induced by a seaway, ship control system interactions or may have been induced by nonlinear interaction of the seaway with the ship. Since seaway measurements were not made during these trials, there was no way of knowing with certainty the cause of these motions [5].

On further study, it was shown that ship motion responses, in most conditions, were small, generally in phase with each other and motion periods consistent with the encountered seaway. This implies that the motions were generally linear, uncoupled responses to the encountered seaway. Roll motions recorded during some of these events were not consistent with the other motions and were large enough to limit MQ-8B operations. It has been hypothesized that these large roll motions may be due to: undetected oblique swell exciting roll motions, interactions of the ship control system with the encountered waves.
causing roll in response to steering nozzle activity or some other roll phenomena due to the LCS designs. Both variants demonstrate a lack of roll damping. These two designs, initially intended to operate at high speed, lack roll damping appendages normally installed for low speed seakeeping performance. This can lead to unexpectedly large roll motions under the right combination of wave field, ship speed and possibly autopilot control.

In addition to ship motion, the unsteady aerodynamic environment in the vicinity of the landing deck can have a profound impact on the aircraft’s flight characteristics. The on deck measurements of the air wake velocities at key locations over the flight deck during operating conditions match those of the aircraft recovery, and can provide valuable information to evaluate aircraft expected responses during recovery.

The implications for Fire Scout operations encountering a resonance response for roll motion, particularly on recovery, is a concern for the PMA. The need for a complete understanding of the ship’s motion characteristics are being driven by ship operational considerations: limited manpower availability, a requirement to reduce the time needed to execute aircraft launch and recovery (L&R) and/or to maintain deck tempo. To facilitate the upcoming ship-suitability assessment, a parallel effort was initiated to determine the feasibility of applying simulations and plug-and-play mission module options in support of unmanned DI at-sea testing and experimentation. Initial analysis indicates traditional linear ship motion models do not predict the presence of roll. Real time measurements appear to offer one of the few choices available to assign a cause to observed, adverse roll motions.

**Legacy Launch and Recovery**

On legacy ships like Guided Missile Frigate (FFG-8) (Oliver Hazard Perry) aircraft stability at touchdown on or near the deck in real-time is calculated using ship motion as a function of the aircraft model [6]. The aircraft model is considered an extension of the ship. The aircraft experiences ship transferred forces and moments, which create rectilinear and angular accelerations on the air vehicle. The accelerations can be numerically integrated to determine the position and attitude of the helicopter relative to the ship as a function of time for various ship motions. This is the inspiration to use the Energy Index (EI) today, to measure and predict deck motion to complete launch and recovery events [7]. Figure 2 displays EI based measures from a test of the MQ-8B Fire Scout aboard USS MCINERNEY (FFG 8).

![Figure 2 – Motion Characterization](image)

The Quad chart shown in Figure 2 contains a time history trace containing rise and fall time events along with the corresponding ship pitch and roll traces. For an eventual auto-land system to function, an auto-land command would be sent to the air vehicle during hover in an appropriate designated position over the deck. Assuming a descent rate similar to other maritime helicopters, the aircraft touches down well within the rise time of the ship. Still referring to Figure 2, the lower left corner of the Quad chart displays a typical 24-hour period of ship motion recordings showing the distribution of deck energies per hour recording, and the hours in which flight operations occurred.

The time required to raise the deck from minimal motion to unacceptable motion is called the rise-time. The rise-time is a thumb print characteristic of the ship's response and rarely changes. In terms of the energy index scale, it is defined as the period of time that is measured from the
end of a green signal to the positive side of the red line. The rise-time is mirrored by a drop time, which is the time period measured from the negative side of the red line to the negative side of the green line. A typical trace as recorded, is displayed in Figure 3.

Figure 3 – Rise-time events in FFG file

The example shows a roll axis divergence eventually exceeding the MQ-8B deck roll limit of 5.0 degrees. In this case the time it took for the deck to rise from quiescence was 18 seconds. There appears to be a 1° roll list to port whilst pitch appears to be essentially in trim. The impulse converges in a fall time measuring 15 seconds. Interestingly, the index exceeded 10.0 prior to the roll axis exceeding the max deck motion limit. Figure 4 displays the deck motion rates for the same time period.

The Y’ axis diverged like roll, but is 1/4 cycle out of phase with roll. There was sufficient energy on the second limit crossing to cause a roll strong enough to exceed deck limits. This is another example of the axial coupling between Y’ and roll. During this test, the ship managed to record at various points 18.9° roll, 4.7° pitch, 2.3 m/s Z’ vertical rate, and 2.7 m/s lateral rate maximum deck displacement.

Figure 4 – Corresponding rise-time rates

Launch and Recovery on New Ship Designs

Recorded shipboard data are often compared with related information from other sources such as the National Data Buoy Center run by National Oceanic and Atmospheric Administration (NOAA). The sea surface and atmospheric data frequently explains the recorded ship data.

As typical in envelope expansion trials, the first class of evolutions are constrained both in environmental and ship motion limits. Over time envelope expansion trials, limits were relaxed as the UAV System proved to operate safely in increasingly difficult conditions. As envelope expansion continued to develop, unexpected ship motion recordings and unusual air wake observations began to accumulate. Figure 5 displays a typical hour file recorded in which excessive motions were recorded. Of particular note (green) were the extent of roll cycles in what appeared to be low sea conditions. Figure 6 displays a recent typical newer Fire Scout (MQ-8C) recovery [8].
Examining the related traces (figures 5, 7, 8), and lining up the graphs (figure 9), it would appear a rare event occurred in which all the degrees of freedom appear to be in phase, but only roll contains sufficient energy to move the ship beyond the MQ-8 landing limits.

On closer inspection, it was determined this event was not an isolated case. Figure 10 displays other examples of rise time events composed of in-phase axial motions even those that are diametrically opposed.
Figure 10 – Similar excessive roll events

Table 2 lists the motion statistics for one of the LCS DI trials.

Table 2 – DI Trial Motion Statistics

According to the NOAA wave charts based on local wave buoy data, the test box off of California was experiencing sea states 0 – low sea state 3. Yet the LCS platform recorded a 10° roll. There was motion along the other degrees of freedom but nothing to support a 10-degree roll. Lateral and vertical rates never exceeded the respective deck limits of the MQ-8. Based on the statistics table, only roll exceeded deck limits of the MQ-8B.

These classes of ship appear to be very stable and capable of maintaining a strict adherence to a heading and speed. This is a basic requirement for aircraft at-sea launch and recovery. However, in order to maintain a lock on heading, jet-pod corrections are made, sometimes in rapid succession. These corrections may be linked to the ship’s autopilot or ride control or both. The impact on UAV flight operations which follow the deck, as seen in figure 11, may cause corrections in the air vehicle glide slope or flight path. These rapid corrections are informally termed ship induced oscillation (SIO).

Figure 11 – Fire Scout respond in roll cycle

The new classes of ship may not resemble several of the air wake and ship motion characteristics of the legacy Navy. Study of these characteristics are necessary in order to better program the UAV system to accommodate these behaviors.

DEFINING SHIP CHARACTERISTICS

With the definition of the LCS in digital form, it should be possible to adjust the various programmed approaches and procedures to accommodate the ship’s motion and over-deck vortex structures leading to improved operational efficiency; specifically, less time the ship has to remain on course for flight ops and maintain personnel at flight quarters.

With a better digital model of the ship’s behavior in various sea conditions, it should be possible to integrate deck motion into aircraft simulations that will allow more preliminary DI testing in a lab environment and reduce the number of test points required to be completed in flight.

With the validation of the digital ship model, aircraft systems software may be updated to accommodate the ship’s behavior on and over the deck leading to safer launch and recovery events through higher sea conditions.

With the platform fully defined, anticipation of the expected deck conditions may lead to better
launch and recovery process planning improving unnecessary heavy deck landing or over-torque of air vehicle engines. This improves the quality and system services impacting maintainability and reliability of the system. Improved ship platform definitions will lead to a shorter learning curve for operators.

There are other non-legacy type vessels being introduced into the fleet to which MQ-8 Fire Scout is expected to be deployed. The trials which have been planned, developed, and executed in the LCS case may prove to be a blueprint to more efficiently characterize the ship’s environmental responses to improve successful system deployment.

The enhanced DI tests are designed to reduce the number of unknown related functional variables that have not been verified by the standard NATOPS trials. Careful analysis of the seaway to include currents, swells, directions, and speeds along with significant wave heights and their periods, are required to gain the complete picture or definition. To this point, much of the analysis has been using motions in the ship coordinate system without attentive documentation of the ship’s heading and speed relative to any existing seaway.

Envelope expansion DI trials are expected to be conducted with an MQ-8C on board the LCS class vessels later this year. The test instrumentation supporting this task include ship motion recording devices. The recordings from these trials will join the library of ship motions data already in existence. Coupled with these recordings, careful attention will be paid to maintaining an eye on the ships speeds and headings.

This is combined with external seaway recordings both from “nearby” anchored wave buoys managed by NOAA and close up wave buoy information recorded by University of California San Diego’s (UCSD) Scripps Institution of Oceanography.

In addition, airflow over the deck and the disturbances created by the ship’s motion behavior will be documented using traditional anemometer towers placed strategically on the flight deck. It is hoped the vortex structures developed by certain relative wind angles and speeds passing over the ship’s solid structures, might be identified. The recorded data will be used to further study this air wake using Computational Fluid Dynamics (CFD) analysis.

**FUTURE WORK AND CONCLUSIONS**

A key user requirement of any naval aviation or small surface embarked boat is the ability to launch and recover the vehicle in high sea states. In high sea states it is known that there are periods of time when a ship's motion alternates between large and more modest excursions. One means of improving the safety of high sea state recovery is to predict when such quiescent periods of ship motion will occur and their duration.

A Quiescent Period Prediction (QPP) system achieves this by using a wave sensor system to measure the sea surface several hundred meters in advance of the ship. From the measured sea surface, a short-term deterministic wave model can be constructed allowing the wave system to be propagated to the ship's location. The ship's response to the wave spectrum is calculated to determine the level of quiescence at the time of encounter. A key part of the system is the wave sensor device, which can be composed of Light Detection and Ranging (LIDAR) or Radio Detection and Ranging (RADAR). A LIDAR system will require a mechanism to scan a laser beam over the sea surface, whereas a radar system can cover a larger area with a single radar pulse.

A speed-polar representation of the seaway to guide ship’s command and deck hand activity, appears as a synoptic map created by the lay-over of various measured and computed parameters. Each parameter speed-polar lay-over is application specific computed as a function of the acceptability of ship’s conditions to complete a specific motion sensitive task (figure 12).
A limit is defined by the impact that a certain ship motion condition may impose on the air/ship vehicle’s structural integrity or that may result in undesired dynamic response. The sum of these lay-overs produces an active operator’s guidance map (figure 13). All of the various QPP components either exist or require limited developmental modification.

Parts of the MQ-8 future improvements involve the enhancement of the associated system components, such as that being done for the L&R segment. The primary goal for conducting DI analysis is to expand existing operating envelopes and increase AV’s availability thereby improving overall naval effectiveness. The objective of DI is to determine the maximum safe air vehicle/ship platform operational limitations.

Given an air/ship system and inherent operational limitations, DI strives to increase tactical flexibility for any set of environmental conditions. Modeling and Simulation complements DI testing to delineate system limitations. The calculated system limitations provide experimental DI with the necessary data to more effectively set testing strategy to probe expected limiting conditions.

This paper provides a discussion of the improvements associated with the MQ-8 system focusing on the L&R process and equipment. These improvements are driven by a need for L&R systems requiring few or no people to operate; systems requiring reduced time to execute high tempo L&R on the deck; systems that provides improved reliability whilst being simple to maintain. One potential problem that could seriously affect MQ-8’s L&R on both of the LCS class ships is the large magnitude of roll experienced in seemingly benign sea conditions. This phenomenon should be further investigated to determine its cause, whether by a swell or parametric conditions, so that it possibly can be avoided.

There has been a great deal of interest in this project from its inception. The team looks forward to providing a status update at the conclusion of the development and start of deployments.

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