Dynamic Interface Testing of Unmanned Aircraft Systems

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ABSTRACT

Since 1943, manned rotorcraft have dominated US Navy ship suitability "Dynamic Interface" (DI) testing. With the recent advances in Unmanned Aerial Systems (UAS), a transition to unmanned rotorcraft DI testing is taking place. This paper presents the experience gained from DI testing of the MQ-8B Fire Scout rotary wing (RW) Unmanned Aerial Vehicle (UAV). Differences in test methodology between RW manned aircraft and UAS are discussed, with a focus on test conditions, rating criteria, instrumentation requirements and data analysis. UAS rotorcraft have introduced launch and recovery task automation and repeatability. These in turn affect the evaluation criteria of the tested wind and ship motion conditions. Evaluation of these tasks is further affected by the absence of airborne pilot qualitative workload assessments. The standard rating criteria for manned rotorcraft – the Deck Interface Pilot Effort Scale (DIPES) and its predecessor, the Pilot Rating Scale (PRS) – are reviewed and compared to the criteria used during MQ-8B DI tests. Standard instrumentation systems and post-test analysis methods used in manned rotorcraft DI testing are reviewed and compared with those used in UAV rotorcraft DI tests.

ACRONYMS

AHS	American Helicopter Society
AV	Air Vehicle
AVO	Air Vehicle Operator
C2	Command and Control
COTS	Commercial off the Shelf
DFCS	Digital Flight Control System
DI	Dynamic Interface
DIPES	Deck Interface Pilot Effort Scale
DMC	Deck Motion Compensation
ESO	External Safety Observer
FFG	Guided Missile Frigate
FQ&P	Flying Qualities and Performance
FTIP	Flight Test Interface Panel
MCS	Mission Control Station
HQR	Handling Qualities Rating

HX-21	Air Test and Evaluation Squadron Two One
ICS	Intercom System
IFC	Interim Flight Clearance
GNC	Guidance Navigation Control
GW	Gross Weight
L/R	Launch/Recovery
NAWCAD	Naval Air Warfare Center Aircraft Division
NVD	Night Vision Device
PIO	Pilot Induced Oscillations
PINS	Portable Instrumentation System
PRS	Pilot Rating Scale
RW	Rotary Wing
RWATD	Rotary Wing Aircraft Test Directorate
SBIR	Small Business Innovation Research
SETP	Society of Experimental Test Pilots
SFTE	Society of Flight Test Engineers
T&E	Test and Evaluation
T/M/S	Type/Model/Series
TCS	Tactical Control System
TDP	Touchdown Point
TM	Telemetry
TS	Track Subsystem
TTCP	The Technical Cooperation Program
UAS	Unmanned Aerial Systems
UASTD	Unmanned Aerial Systems Test Directorate
UAV	Unmanned Aerial Vehicle
UCARS	UAV Common Automatic Recovery System
VERTREP	Vertical Replenishment

1.0 INTRODUCTION

The US Navy began conducting rotorcraft ship suitability testing in 1943 with the Sikorsky XR-4 helicopter landing aboard the SS BUNKER HILL (Figure 1, reference 1). Starting in 1949, shipboard tests were conducted by the rotary wing section of the Naval Air Test Center until 1975, when the Rotary Wing Aircraft Test Directorate (RWATD) was established. The Test Directorate became the Rotary Wing Test Squadron, and in 2002 was renamed Air Test and Evaluation Squadron Two One (HX 21). With the recent increase in Navy UAS programs, the Unmanned Aircraft Systems Test Directorate (UASTD) was established in 2010 to assume the role of UAS Test and Evaluation (T&E). MQ-8B T&E was transferred from HX-21 to the UASTD. Today UAV DI engineering support is provided by the Naval Air Warfare Center Aircraft Division (NAWCAD) RW Ship Suitability Branch. This branch is informally known as the DI branch, referring to testing the dynamic interaction between rotorcraft and ships at sea. Specifically, DI testing focuses on investigation of the relative wind and ship motion conditions that define the safe limits for rotorcraft launch and recovery shipboard operations. The aircraft test data analyzed by DI traditionally include handling qualities, performance, and pilot workload. Quantitative and qualitative data are collected in the form of cockpit and instrumentation parameters and observations regarding pilot visual cues, sea spray, funnel exhaust, and related factors affecting pilot workload.

Figure 1: Sikorsky XR-4 shipboard landing demonstration aboard SS BUNKER HILL, 1943.

From the early 1970’s until the mid-2000’s, DI testing was conducted with manned helicopters utilizing primarily the PRS, a simplified four-point derivative of the 10-point Cooper-Harper Handling Qualities Rating (HQR) Scale (reference 1). Other rating scales have been developed and utilized to supplement the PRS, such as the turbulence, vibration, and Pilot Induced Oscillations (PIO) rating scales. In 2001, the US Navy adopted a new five-point rating scale, the DIPES, as an outcome of The Technical Cooperation Program (TTCP). TTCP was tasked to improve cooperation in science and technology between the United States, the United Kingdom, Canada, Australia, and New Zealand. The US Navy fully transitioned from the PRS to the DIPES in the mid-2000’s.

While shipboard landing demonstrations were performed in 1963 with the QH-50 DASH (Figure 2, reference 2), in 1991 with the CL 227 Sentinel, 1999 with the CL 327 Guardian, and in 2006 with the RQ-8A early variant of the Fire Scout, full-scale DI testing had not been conducted with unmanned rotorcraft until 2009. The Navy’s first modern UAV DI test took place during four underway periods in 2009 aboard USS MCINERNEY (FFG 8) with the MQ-8B Fire Scout (Figure 3). These initial tests required a new test methodology (reference 3) to evaluate Flying Qualities and Performance (FQ&P) at various ship-relative wind and ship motion conditions, and to develop operational envelopes.

Figure 2: QH-50 DASH Testing aboard US Navy Destroyer.

Figure 3: MQ-8B Fire Scout Initial Ship Suitability Testing aboard USS MCINERNEY (FFG 8).

2.0 MANNED RATING SYSTEMS

Since the beginning of RW shipboard testing, DI engineers have relied on pilot qualitative observations to complement quantitative data for assessing test conditions. Prior to 1974, pilots utilized the Cooper-Harper HQR scale to assess handling qualities for DI tests. In time, however, it became apparent that the HQR scale was optimized for singular tasks, and was cumbersome in defining the entirety of the multi-axis, multi-task workload of the compound shipboard launch and recovery tasks. A result of this finding, an abbreviated scale was developed, the PRS (Table 1). Firstly, the PRS contains two ratings for slight and moderate pilot effort, PRS 1 and PRS 2. Both of these ratings denote ship-relative wind regions considered safe for inclusion in the Launch/Recovery (L/R) envelope for use by fleet pilots. PRS 1 and PRS 2 ratings provide nuanced detail in the assessment of an acceptable test condition by subdividing the range of acceptable conditions into two ratings. Secondly, the PRS scale contains one rating, PRS 3, for maximum pilot effort that is not considered safe for inclusion in the L/R envelope for fleet pilots, but sufficiently safe for repeat testing by trained test pilots at that condition. A previously tested condition may be repeated to verify repeatability of the pilot effort and/or aircraft response at that condition, and to confirm the initial pilot rating. Thirdly, the PRS scale contains one rating, PRS 4, for unsatisfactory pilot effort. The PRS 4 rating excludes that test condition from the L/R envelope for fleet pilots, and prohibits it being retested by trained test pilots.

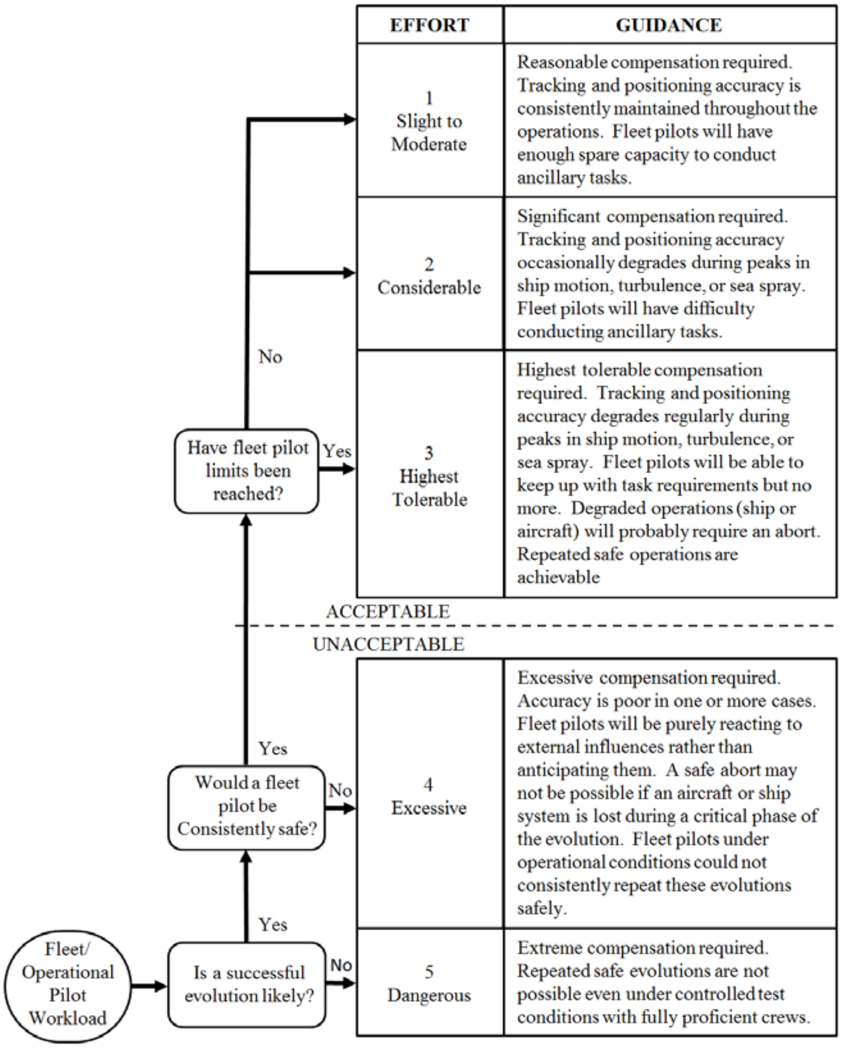
Table 1: Pilot Rating Scale

PRS # Pilot Effort	Rating Description
1 Slight	No problems; minimal pilot effort required to conduct consistently safe shipboard evolutions under these conditions.
2 Moderate	Consistently safe shipboard evolutions are possible under these conditions. These points define the fleet limits recommended by NAWCAD PAX RIVER.
3 Maximum	Evolutions are successfully conducted only through maximum effort of experienced test pilots using proven test methods under controlled test conditions. Successful evolutions could not be consistently repeated by fleet pilots under typical operational conditions. Loss of aircraft or ship system is likely to raise pilot effort beyond capabilities of average fleet pilot.
4 Unsatisfactory	Pilot effort and/or controllability reach critical levels; repeated safe evolutions by experienced test pilots are not probable, even under controlled test conditions.

With the adoption of the DIPES rating scale (Table 2), the most notable difference from the PRS rating scale is that the DIPES provides an additional subdivision of test conditions considered acceptable for inclusion in the L/R envelope for fleet pilots. This change was made for commonality between US Navy pilot ratings and those of the participating TTCP nations. DIPES 1 (Slight to Moderate), DIPES 2 (Considerable), and DIPES 3 (Highest Tolerable) all represent various levels of acceptable fleet pilot workload. The DIPES 4 rating is similar to the PRS 3 rating in that the condition is considered safe for repeat by test pilots under controlled test conditions, but not for inclusion in the L/R envelope for fleet pilots. As in the case for repeating a PRS 3, the purpose for repeating a DIPES 4 condition is to verify the data collected and the initial rating given. The DIPES 5 rating is similar to the PRS 4 rating in that the condition is considered unsafe for repeat by trained test pilots and excludes it from the L/R envelope for fleet pilots. The additional point in the DIPES scale was added along with a list of suffices describing contributing factors to the pilot workload, in order to provide greater detail in capturing the conditions and causes of each given rating. Increasing the number of safe or “acceptable” rating points from two to three improves the ability to track trending patterns as relative wind and/or ship motion conditions change during test buildup. Adoption of the DIPES rating scale also brought US Navy commonality with the participating TTCP nations.

Since both the PRS and DIPES rating scales focus on pilot qualitative assessment of workload, quantitative measurements are normally added to the assigned ratings to define the tested condition as falling within or outside of safe and repeatable limits for fleet operators. For example, a minimum of 10% power/torque or control margins is generally required for inclusion in the approved envelope (references 4, 5). In the case of a pilot rating the workload as slight (DIPES 1) while using sustained 94% directional control input in the hover, the tested condition will likely be considered outside of the L/R envelope.

Table 2: Deck Interface Pilot Effort Scale



EFFORT	GUIDANCE
1 Slight to Moderate	Reasonable compensation required. Tracking and positioning accuracy is consistently maintained throughout the operations. Fleet pilots will have enough spare capacity to conduct ancillary tasks.
2 Considerable	Significant compensation required. Tracking and positioning accuracy occasionally degrades during peaks in ship motion, turbulence, or sea spray. Fleet pilots will have difficulty conducting ancillary tasks.
3 Highest Tolerable	Highest tolerable compensation required. Tracking and positioning accuracy degrades regularly during peaks in ship motion, turbulence, or sea spray. Fleet pilots will be able to keep up with task requirements but no more. Degraded operations (ship or aircraft) will probably require an abort. Repeated safe operations are achievable
4 Excessive	Excessive compensation required. Accuracy is poor in one or more cases. Fleet pilots will be purely reacting to external influences rather than anticipating them. A safe abort may not be possible if an aircraft or ship system is lost during a critical phase of the evolution. Fleet pilots under operational conditions could not consistently repeat these evolutions safely.
5 Dangerous	Extreme compensation required. Repeated safe evolutions are not possible even under controlled test conditions with fully proficient crews.

Note: Each DIPES rating may be given one or more suffices to describe the cause(s) of the increased workload.

Visual Cues: V
Roll Control: R
F/Aft Positioning: F
Lateral Positioning: L
Spray: S
A/C Attitude: A
Height Control: H
Deck Motion: D
Yaw Control: Y
Turbulence: T
Pitch ControL: P
Tq/Eng Control: Q
Funnel Exhaust: E

3.0 MANNED DI COMMON INSTRUMENTATION

Common quantitative DI test parameters include engine power, transmission torque, collective, directional (pedal) control, lateral and longitudinal (cyclic) control, and fuel state for Gross Weight (GW) calculation. Various methods have been used for obtaining these basic parameters throughout the diverse Type/Model/Series (T/M/S) of rotorcraft tested through the years. In early aircraft, the majority of US Navy helicopters were not equipped with Digital Flight Control Systems (DFCS) or with any other means for readily obtaining the needed flight controls parameters. DI testing typically required the copilot to monitor and document torque and fuel state on the instrument panel. The remaining parameters were often obtained through rudimentary methods such as tape measures attached to the cyclic and collective control sticks and tail rotor control pedals.

To assist the copilot in documenting the data in real-time, Commercial Off-the-Shelf (COTS) analog voice tape recorders connected to the cockpit Intercom System (ICS) were often used. Instrumentation systems common to all T/M/S rotorcraft were difficult to develop due to the absence of built-in digital or analog data sources in older designs. An attempt at a common DI instrumentation system was a Small Business Innovation Research (SBIR) device called the Portable Instrumentation System (PINS). PINS employed ultrasonic pedal position sensors for directional control displacements, and a cockpit video capture system for analog-to-digital conversion of parameters displayed on the pilot instrument panel. Once installed, the pedal position sensors provided data without further problems, although installation in each of the various T/M/S varied and required development of installation procedures and extensive Interim Flight Clearance (IFC) airworthiness documentation. The video capture required development and verification of analog-to-digital data conversion software, for which sufficient time and funding were limited.

An early advance in rotorcraft DI instrumentation became available in the SH-60F Seahawk helicopter that was equipped with a Flight Test Interface Panel (FTIP). A data recorder could be connected to the FTIP relatively easily, and record a limited number of test parameters. A significant improvement in instrumentation became possible with newer rotorcraft designed with DFCS. A DFCS allows digital instrumentation systems to connect directly to the data bus to monitor and record bus traffic for most or all required DI parameters. These systems facilitate both real-time monitoring via telemetry (TM) and post-flight processing via onboard data recorders. The MV-22B Osprey tiltrotor was one of the first rotorcraft to employ digital data recording and real-time TM transmission of all required DI aircraft parameters. While pilot ratings are still used, the TM data provides essential real-time monitoring of each test point, and the recorded data help to better define each condition within the tested wind regions. These instrumentation systems often reveal information that is transparent to the pilot, such as control command saturation, that may not be detected by aircraft state or control force feedback. A DFCS also makes it possible to design and build common instrumentation systems for the various T/M/S employing these digital control systems. All unmanned rotorcraft use DFCSs that allow digital recording of instrumented parameters. UAVs require TM or sufficient downlink capability for real-time monitoring to enable effective real time assessment and safe test buildup.

4.0 MANNED AND UNMANNED DIFFERENCES

4.1 Manual/Autonomous/Semi-Autonomous Control

While manned rotorcraft are controlled by onboard pilots, UAVs are controlled by an Air Vehicle Operator (AVO) via a Mission Control Station (MCS). Onboard pilots make manual control inputs in all three axes (lateral and longitudinal cyclic, directional, and power/collective). AVOs exercise varying levels of direct/indirect control of the UAV depending on the specific UAS design. In the case of the MQ-8B, the

Command and Control (C2) system is semi-autonomous. AVO C2 is not directly uplinked to the air vehicle (AV) flight controls, but is instead transmitted from the MCS Tactical Control System (TCS) to the AV Guidance Navigation Control (GNC) computers. The AVO exercises two primary control modes: Program Mode utilizes pre-planned mission plans comprised of multiple waypoints, defined by location (latitude/longitude), altitude, and airspeed; while Vector Mode utilizes real-time AVO commands to set AV course, speed, and altitude. UAVs developed for shipboard operations increasingly use semi-autonomous flight functionality for the ship L/R tasks. Because of the increasing levels of automation (reference 6) of the shipboard L/R tasks in modern RW UAVs, evaluation of UAV DI test evolutions focus on analysis of the automatic or semi-automatic system performance and disturbance response rather than the human operator workload similar to that applied throughout the rich heritage of carrier-based automatic landing of fixed wing aircraft (reference 7).

4.2 Rating Criteria

Since unmanned aircraft have no onboard pilot, qualitative assessments or ratings from the airborne perspective are not possible. Evaluation of each test condition (mainly wind and ship motion) relies primarily on quantitative data obtained through real-time TM monitoring complemented by shipboard visual observations, inertial systems, and by External Safety Observers (ESOs). For UAS DI, pilot real-time qualitative observations are replaced by real-time TM monitoring by experienced engineers' quantitative and qualitative assessments. Quantitative assessments focusing on common quantitative DI test parameters, actuator displacements, and other key control system parameters become the primary means of determining the proximity to loss of control conditions. Pilot judgment is replaced by AVO and engineering judgment through close monitoring of not only individual parameters and test limits, but on aggregate trending in both short term (during individual L/R events) and long term (over several test conditions during test buildup).

4.3 Variability

Manned rotorcraft are flown by individual pilots with varying experience, skill, and technique. In addition to individual piloting differences, the various services often provide different training and technique. An example is the Vertical Replenishment (VERTREP) task, where US Marine Corps pilots normally orient the aircraft parallel to the ship while US Navy pilots pick up the load at right angles with the ship. As described previously, UAVs may incorporate direct control by a remote pilot, which introduces individual operator variability similar to manned rotorcraft, or may incorporate various levels of autonomous flight that reduce individual operator variability. The level of autonomous or semi-autonomous C2 during the shipboard L/R tasks is critical when assessing DI test data. In the case of the MQ-8B, shipboard L/R involve a very limited number of discrete AVO commands that trigger specific autonomous tasks. While on deck, the launch task requires that the AVO issue a Launch command to lift the AV to a Launch Perch position over the deck, and then a Perch Proceed command to initiate departure. Similarly, while at a Recovery Perch position aft of the touchdown point, the recovery task requires that the AVO issue a Land command to initiate the terminal approach, hover, and landing sequence. Outside of these AVO commands, the MQ-8B L/R tasks are fully autonomous. Therefore, unlike manned rotorcraft, autonomous UAV flight paths relative to the ship are not influenced by individual pilot variability factors such as training, technique, skill, experience, fatigue, etc. L/R task variability is only limited to system compensation for environmental effects such as airwake turbulence and ship motion. While UAV testing lacks pilot assessments, the reduced variability in AV flight path and state aids TM engineers and external observers in the evaluation task by making anomalous AV behavior easier to detect externally to the AV.

4.4 Visual Cues

Manned rotorcraft DI includes assessing the visual cueing environment, a major contributor to pilot workload. This involves assessing the visual cues related to the deck markings, day operations, night unaided operations, Night Vision Device (NVD) aided operations, and pilot/copilot (right seat/left seat) perspectives. Without an onboard pilot, semi-autonomous UAVs such as the MQ-8B do not currently rely on visual cues to recover or launch aboard ship. All operational US Navy autonomous UAV ship landing systems to date use a combination of radar/microwave subsystems and inertial systems to autonomously guide the AV to the deck. The MQ-8B receives ship-relative position data from a ship-mounted UAV Common Automatic Recovery System (UCARS) Track Subsystem (TS). Some early development work for the UCARS can be found in reference 8. As a result, rating test conditions for UAV DI generally does not include visual cues, and separate night testing is not required as part of L/R envelope expansion testing. First-of-Class testing on new ship types generally includes one night test flight to identify potential unanticipated issues in areas such as pre-flight and post-flight deck operations or AVO and ship crew situational awareness and communications.

4.5 Instrumentation

Newer rotorcraft offer easier and more accurate measurements and recording, using either built-in production recording capabilities or onboard digital instrumentation systems passively collecting data from the databus or dedicated test sensors. All unmanned rotorcraft use DFCSs that allow digital recording of instrumented parameters. Without any aircrew providing real-time reporting, UAV DI requires TM or sufficient downlink capability for real-time monitoring to enable effective real time assessment and safe test buildup.

4.6 Ship Motion Parameters

Manned RW L/R envelopes are defined by ship-relative wind limits as well as ship motion limits in the form of maximum pitch and roll amplitudes. Pitch and roll have been sufficient for characterizing the deck dynamics with respect to current pilot workload constraints in the approach, hover, and departure phases of flight. Pilots assess ship motion while striving to time the liftoff and touchdown between larger intensity deck oscillation periods in order to mitigate potential hazards. Pilot comfort level may also be affected by deck motion with the aircraft on deck and unrestrained, which can factor into the assessment of deck motion limits. Pilot error can be introduced when the pilot attempts to chase the deck during hover or during climb or descent. Also, the existence of pitch and roll limits is consistent with older ships that lack modern inertial measurement sensors, often being equipped with only bubble inclinometers. The MQ-8B L/R functionality is automatic, which requires precise relative position and inertial sensing. Consequently, all ship motion degrees-of-freedom are typically monitored more closely than in the case of manned systems in order to properly evaluate the system performance and its ability to execute the ship L/R tasks.

Ship motion limits for safe and effective automatic L/R of RW aircraft are not completely addressed by pitch and roll alone because of the design of the systems themselves, which utilize airborne and shipboard sensor information to meet more stringent performance requirements. What the pilot otherwise does when synchronizing the manned AV to the movement of the deck is replaced by an automatic system that must execute the same task for the unmanned AV with much improved accuracy and repeatability. This inherently requires monitoring of information that may otherwise be unavailable or not readily available to the pilot of a manned system. The MQ-8B recovers under UCARS control during final approach to touchdown. Upon vertical descent to the deck, Deck Motion Compensation (DMC) is activated in order to synchronize the AV with the motion of the Touchdown Point (TDP). The DMC is also activated at the time of launch in order to reduce the impact of ship motion during launch. The AVO monitors TDP surge and sway and relays to the bridge crew, who have only ship pitch and roll indications available. Large TDP surge, sway, and/or heave motion can occur even when pitch and roll conditions are within approved limits, which, when coupled with potentially adverse impacts of the ship airwake, may increase the potential for unsafe conditions at launch and/or during wave-off in close proximity to the deck. Consequently, excessive TDP motion can place the system outside of safe L/R limits, which requires that ship motion limits be delineated to include the motion of the targeted deck TDP as well as pitch and roll.

4.7 Launch and Recovery Tasks

Despite manned/unmanned differences in system functionality, the basic launch and recovery tasks remain the same. In the case of the MQ-8B, the approach and departure profiles tested to date are similar to manned rotorcraft profiles. DI testing evaluated stern and oblique approaches. Launches were tested with initial launch orientation aligned fore and aft with the ship followed by launch and pedal turn for departure, and with initial oblique launch orientation followed by launch and pedal turn for departure. Other approach/departure profiles common with manned helicopters are also possible with UAVs and have been considered, such as heading offset from the relative approach course and departures with lateral sidestep. These profiles have not been tested to date.

4.8 Operational Procedures

Operational launch and recovery procedures are very similar between manned and unmanned rotorcraft, with the exception of the pilot being replaced with the AVO and the ESO. Crew communication, deck status, and aircraft handling procedures, including deck restraints, fueling, and respot, are essentially identical in the case of the MQ-8B.

4.9 DI Test Method and Buildup

For both manned and unmanned DI, the basic approach to L/R envelope expansion testing consists of sequential launch and recovery evolutions with incremental relative wind buildup. Relative wind is changed in increments of 15° or 5 knots, and ship motion is allowed to increase in increments of no more than 2° in each (pitch and roll) axis. One notable difference with MQ-8B DI is that for winds greater than 20 knots, test points at each wind azimuth require a previously tested point with wind speed 5 knots lower, and rated Acceptable. This requirement was adopted as an additional precaution to real-time TM monitoring. This was partly due to MQ-8B directional control sensitivity in right crosswinds as observed in shorebased testing, and partly due to cautious concern of rapidly approaching torque or control limits within the 5 knot or 15° buildup increments. As DI continues and matures with the MQ-8B and other UAS, this slower cautious build-up requirement may be reduced or lifted. It should be kept in mind that modifications to the standard buildup criteria are not driven exclusively by the absence of a pilot, and are not unique to the MQ-8B. For example, MV-22B buildup has been similarly restricted due to lateral axis handling qualities characteristics.

4.10 Critical Test Parameters

The primary indications of wind effects are common to manned and unmanned aircraft. Lateral and longitudinal cyclic, directional, and power/torque margins are critical common aircraft performance parameters. While additional SOF/SOT parameters are monitored on UAVs to provide additional insight on system performance, the flight controls and power/torque are still considered to be the primary parameters that define all rotorcraft safe and repeatable limits of the operational L/R envelope.

4.11 Relative Wind and Ship Motion Limits

L/R envelopes for the MQ-8B have been approved and published for the FFG 7 and LCS 1 (references 9, 10) classes of ships. The envelopes contain the same type of wind and ship pitch and roll parameter limits as are provided for manned rotorcraft, except that additional ship surge and sway limits have been added. Given the lack of ship surge and sway motion indication on the ship bridge, the AVO is tasked to monitor these parameters and confirm to the bridge crew that the system is within parameters for launch or recovery. Ship crews can utilize MQ-8B envelopes without any additional instruction.

5.0 UAS RATING SYSTEM

Test planning for the first MQ-8B DI in 2009 recognized that the traditional method of classifying the tested condition into Acceptable (PRS 1 2, DIPES 1 3), Marginal (PRS 3, DIPES 4), and Unacceptable (PRS 4, DIPES 5) was equally useful and appropriate for UAV DI. It was noted that the distinctions amongst the Acceptable ratings for manned rotorcraft were driven primarily by pilot qualitative observations with a focus on pilot workload. The test team concluded that the AVO, located inside the ship and commanding autonomous recovery and launch tasks, was not in a position to provide useful qualitative ratings within the Acceptable range. Further, it was recognized that UAV ratings would not be measures of pilot workload, but of system performance. With these differences in mind, consideration was given to replacing the pilot qualitative DIPES 1-3 ratings with TM engineer qualitative ratings based on observation of the TM parameter traces throughout each recovery and launch task. It was decided that, while TM engineers could reliably determine whether a test event was safe and repeatable, there was not sufficient benefit for them to divide the safe and repeatable conditions into subcategories as is done by pilots during manned RW DI. It was also decided that for the purpose of defining the envelope, the primary classification requirement was Acceptable or other than Acceptable conditions, and that subdivisions within the Acceptable range were unnecessary. The decision was made to adopt one single Acceptable rating.

In the case of other than Acceptable conditions, the MQ-8B test team wanted to retain the distinction between conditions requiring retest to verify whether they are acceptable or otherwise, and those determined by the initial test point to be unacceptable. While this distinction relies on trained test pilots in the case of manned rotorcraft, it relies on trained TM engineers to assess repeatability of a given condition in the case of UAV operations.

All MQ-8B ratings (Table 3) represent the combined quantitative and qualitative criteria. Quantitative criteria consist of flight control margins, power and torque margins, UCARS spatial position errors in flight, touchdown position error, and auto-waveoff. Qualitative criteria consist of engineering assessment of trending of these parameters together with all other designated SOF/SOT parameters (AV state, rates, accelerations, health monitoring, etc.).

Table 3: Fire Scout DI Rating System

ACCEPTABLE	
Control Margins	• ≥ 10% sustained (> 2 sec) remaining • ≥ 5% peak remaining
Engine Torque Margin	• ≥ 10% sustained (> 2 sec) remaining • ≥ 5% peak remaining
Position	• < 2.5 ft X and Y position error during descent below LH • < 2.5 ft X and Y touchdown position error
Automatic Waveoff	No
Trending	Minor adverse trending as determined by TM engineer, AVO, and visual observers.
MARGINAL	
Control Margins	• 5-10% sustained (> 2 sec) remaining • 0-5% peak remaining
Engine Torque Margin	• 5-10% sustained (> 2 sec) • 0-5% peak remaining
Position	• 2.5-3.5 ft X and Y position error during descent below LH • 2.5-3.5 ft X and Y touchdown position error
Automatic Waveoff	Yes
Trending	Moderate adverse trending as determined by TM engineer, AVO, and visual observers
UNACCEPTABLE	
Control Margins	• < 5% sustained (> 2 sec) remaining • < 0% peak remaining
Engine Torque Margin	• < 5% sustained (> 2 sec) • < 0% peak remaining
Position	• > 3.5 ft X and Y position error during descent below LH • > 3.5 ft X and Y touchdown position error
Automatic Waveoff	
Trending	Severe adverse trending as determined by TM engineer, AVO, and visual observers

6.0 POST-TEST ANALYSIS

Post-test data analysis for MQ-8B DI testing involves processing the data into presentable formats and conducting a series of integrated team reviews. Reviews begin with a focus on real-time Acceptable ratings. The initial reviews ensure that all Acceptable ratings are properly assigned based on the rating criteria per Table 3. Subsequent reviews progress to Marginal and Unacceptable ratings, with tasks and additional analysis identified during the process. In cases where the real-time rating should have been Acceptable, those ratings are changed accordingly. In cases where real-time ratings are Marginal but detailed review determines to be safe and repeatable, the conditions are approved for inclusion in the envelope. Unacceptable ratings are also reviewed and considered for reclassification as appropriate, with primary consideration given to ensuring safe and repeatable conditions in the fleet operational environment. This data analysis process is common or similar to the (manned) MV-22B process due to the unique lateral axis handling qualities characteristics of the V-22 DFCS. By comparison, legacy rotorcraft DI data analysis for aircraft with mechanical or hydraulic flight controls normally involves a single round of review.

7.0 CONCLUSIONS

Unmanned RW ship suitability DI testing requires test methodology and standards for determining wind and ship motion operational limits. The basic requirements for manned DI have been reviewed and adapted to those of UAS DI. Unmanned rotorcraft launch and recovery task automation, repeatability and the absence of onboard pilot workload assessments must be addressed in the transition from manned to unmanned rotorcraft DI testing. Primary quantitative data requirements for manned rotorcraft are common to UASs, but pilot duties of monitoring and recording are transferred to TM engineers. Qualitative assessments that were primarily pilot duties are transferred to TM engineers and external visual observers. The evolutions of the various rating scales for manned DI continue with the transition to UAS DI in order to support the unique requirements for unmanned systems. The MQ-8B Fire Scout rating scale is an example of a rating system optimized to assess the L/R tasks of semi-autonomous rotorcraft. Post-test analysis for UAS is generally more in-depth than manned T&E due to the complex flight control systems and more stringent performance requirements.

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REFERENCES

[1] Williams, Suni L. and Long, Kurt R., *Dynamic Interface Flight Test and the Pilot Rating Scale*, AHS 53rd Annual Forum, 29 April – 1 May, 1997, pp. 3, 8-12.

[2] Evans, Samuel S., *The Incredible Story of the QH-50 DASH, Vertiflite*, Spring 2011, p. 38.

[3] Nelson, John and Danielson, Jeffrey, MQ-8B Fire Scout Initial Ship Suitability Tests aboard USS MCINERNEY (FFG 8), NAWCADPAX/RTR-2009/118, 22 August, 2013, pp. 3-6, 86.

[4] Geyer, W.P. Jr., Long, K, Carico, D., *Helicopter/Ship Qualification Testing, Part 2: American Clearance Process*, RTO-AG-300 Vol. 22, AC/323(SCI-038) TP/53, Flight Test Techniques Series – Volume 22, Part 2, February 2003.

[5] Collier, Sean T., *Improved Flight Test Techniques for Evaluating Control Margins in the Shipboard Environment*, University of Tennessee M.S. Thesis, May 2006, pp. 9-11, 13-14, 16.

[6] Ferrier, Dr. B., Sehgal, A., Ernst, R (2014). *FireScout UAV Launch and Recovery System Performance Improvement*, Proceedings of the AUVSI. AUVSI-14.1513-Ferrier. Alexandria, 15 May, 2014, pp. 4-8, 16-17, 19-20.

[7] *Carrier Suitability Testing Manual*, SA FTM-01, Rev 2, 30 September 1994, Sections 11 and 13.

[8] Huff, R.W., Waldron, W.M., and Aksteter, J.W. *Autoland Simulation Studies for Unmanned Aerial Vehicles,* NAWCAD RTR No. NAWCADPAX-94-41-RTR, 31 October 1994.

[9] Polgreen, Andrew and Danielson, Jeffrey, MQ-8B Fire Scout Ship Suitability Testing aboard USS FREEDOM (LCS 1), NAWCADPAXR/RTR-2013/108, 30 May, 2013, pp. 25-26.

[10] Nelson, John and Flagg, Eric, MQ-8B Fire Scout Ship Suitability Testing aboard USS FORT WORTH (LCS 3), NAWCADPAX/RTR-3013/338, 3 November, 2014, pp. 133-136.

BIOGRAPHY

John Nelson is Ship Suitability Engineer for the MQ-8B Fire Scout program. He conducted the first Ship Suitability “Dynamic Interface” flight tests with the MQ-8B aboard guided missile frigate USS MCINERNEY (FFG 8) and Littoral Combat Ships USS FREEDOM (LCS 1), USS FORT WORTH (LCS 3), AND USS CORONADO (LCS 4). He obtained his BS in Mechanical/Aerospace Engineering from Worcester Polytechnic Institute in 1995 and his MS in Aerospace Engineering from Syracuse University in 2000. He has conducted fixed wing and RW shipboard tests since 1998, including seven years on the MV-22B Osprey tilt-rotor program. He has written technical papers and has shared his test experience with the engineering community as a speaker at American Helicopter Society (AHS), Society of Flight Test Engineers (SFTE), and Society of Experimental Test Pilots (SETP) symposiums.