

# INITIAL PROGRESS TO ESTABLISH FLYING QUALITIES REQUIREMENTS FOR MARITIME UNMANNED AIRCRAFT SYSTEMS

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## Abstract

This paper describes the development work being undertaken to establish Flying Qualities Requirements for Unmanned Aircraft Systems (UAS) expected to operate in the Maritime Environment. A UAS Dynamics Model (UDM) has been developed to allow the rapid investigation of the aircraft dynamics required to conduct ship-deck launch and recovery operations. The process used to develop the UDM is described. A typical recovery manoeuvre has been broken down into individual Mission Task Elements. These form the basis for the evaluation of the UDM dynamic responses against task-specific performance criteria. Two stochastic turbulence modelling schemes, the Control Equivalent Turbulence Inputs and Virtual AirDyn methods, have also been developed using previously computed time-accurate air wakes. These air wakes have been integrated into FLIGHTLAB modelling software and extracted using stochastic methods before integration into the UDM modelling environment. The model has been initially configured to assess an SH-60B-class UAS operating from a Type 23 Frigate.

## NOTATION

AC	<i>Attitude Command</i>	$\zeta$	<i>Damping Ratio [nd]</i>
ACP	<i>Airload Computation Point</i>	$\theta$	<i>Pitch Attitude [rad]</i>
AWC	<i>Air Wake Compensator</i>	$\tau$	<i>Time Constant [s<sup>-1</sup>]</i>
CETI	<i>Control Equivalent Turbulence Inputs</i>	$\phi$	<i>Roll Attitude [rad]</i>
CFD	<i>Computational Fluid Dynamics</i>	$\phi_{cmd}$	<i>Commanded Roll Attitude [rad]</i>
DES	<i>Detached Eddy Simulation</i>	$\psi$	<i>Yaw Attitude (Heading) [rad]</i>
DOF	<i>Degrees of Freedom</i>	$\omega$	<i>Natural Frequency [rad.s<sup>-1</sup>]</i>
FCS	<i>Flight Control System</i>	$H(s)$	<i>Turbulence Transfer Function</i>
FQR	<i>Flying Qualities Requirement</i>	$L$	<i>Turbulence Reference Length [m]</i>
GPS	<i>Global Positioning System</i>	$V$	<i>Free-stream velocity [m.s<sup>-1</sup>]</i>
IR	<i>Infra-Red</i>	$X_u$	<i>Longitudinal Damping Derivative [s<sup>-1</sup>]</i>
MTE	<i>Mission Task Element</i>	$Y_v$	<i>Lateral Damping Derivative [s<sup>-1</sup>]</i>
OOC	<i>Out-of-Control Flight</i>	$Z_w$	<i>Normal Damping Derivative [s<sup>-1</sup>]</i>
PID	<i>Proportional-Integral-Derivative</i>	$Z_{\delta COL}$	<i>Heave Response Derivative [m.s<sup>-2</sup>]</i>
PIO	<i>Pilot Induced Oscillation</i>	$g$	<i>Acceleration due to Gravity [m.s<sup>-2</sup>]</i>
PSD	<i>Power Spectral Density</i>	$p$	<i>Body Roll Rate [rad.s<sup>-1</sup>]</i>
RC	<i>Rate Command</i>	$q$	<i>Body Pitch Rate [rad.s<sup>-1</sup>]</i>
RF	<i>Radio Frequency</i>	$q_{cmd}$	<i>Commanded Pitch Rate [rad.s<sup>-1</sup>]</i>
SAS	<i>Stability Augmentation System</i>	$r$	<i>Body Yaw Rate [rad.s<sup>-1</sup>]</i>
SHOL	<i>Ship-Helicopter Operating Limits</i>	$s$	<i>Complex Variable [j<math>\omega</math>]</i>
SIO	<i>System Induced Oscillation</i>	$u$	<i>Longitudinal Body Velocity [m.s<sup>-1</sup>]</i>
SRGPS	<i>Shipboard Relative GPS</i>	$v$	<i>Lateral Body Velocity [m.s<sup>-1</sup>]</i>
TRC	<i>Translational Rate Command</i>	$w$	<i>Normal Body Velocity [m.s<sup>-1</sup>]</i>
UA	<i>Unmanned Aircraft</i>		
UAS	<i>Unmanned Aircraft System</i>		
UCARS	<i>UAV Common Automatic Recovery System</i>		
WOD	<i>Wind-Over-Deck</i>		

## 1. INTRODUCTION

Unmanned Aircraft Systems (UAS) can be used as a cost-effective alternative to undertake many roles traditionally performed by manned aircraft. The removal of the pilot from the aircraft has led to the development of a wide range of UAS types in terms of size, configuration and role. UAS have been heavily utilised in United Kingdom (UK) military theatres of operation, primarily from land-based operating bases. However, research developments in maritime UAS operations are still dominated by the United States (US).<sup>[1][2]</sup>

In recent years, there has been considerable effort to understand the environment around landing decks on naval vessels.<sup>[3]</sup> Of particular interest for manned maritime helicopter operations are the characteristics of the air flow in which they operate, over and around the ship's landing deck. The ship airwake, as it is called, is formed in the lee of the ship's superstructure and is characterised by unsteady flapping shear layers and strong vortical structures. The unsteady airwake increases the pilot workload required to control the aircraft and is one of the limiting factors that define the Ship-Helicopter Operating Limits (SHOLs). For unmanned aircraft, the magnitude and frequency content of this unsteady airwake has a significant impact on the bandwidth requirements for the control system architecture and is further compounded by the changing dynamic characteristics with aircraft size.<sup>[4]</sup> The determination of Flying Qualities Requirements (FQRs) is therefore of the utmost importance for future procurement of a UAS intended to operate in this environment. This paper reports on the early progress of a DSTL-sponsored project at the University of Liverpool (UoL) which aims to address this issue for rotary-winged UAS.

The project has been broken down into the following stages:

1. Development of tools and techniques to investigate UAS FQRs;
2. Validation of FQRs using higher fidelity simulation;
3. Expansion of investigation to assess the impact of rotorcraft size and configuration; and
4. Validation of the investigative tools and techniques using UAS hardware.

The paper reports on early progress in stage 1 of this process and covers the fundamentals of the simulation modelling tools being developed at UoL.

Section 2 highlights some of the challenges that need to be addressed to establish UAS FQRs before

exploring current research in Ship-Helicopter Operations. Section 3 goes on to describe the modelling environment which has been developed to allow an investigation into the dynamic system characteristics that affect UAS capabilities when operating in the maritime environment, before breaking the operations down into individual Mission Task Elements (MTEs) to be used to evaluate FQRs. The paper concludes by presenting two alternative turbulence modelling schemes which will be evaluated during the next phase of the project.

## 2. MARITIME OPERATIONS AND UAS FLYING QUALITIES REQUIREMENTS (FQRs) – CURRENT RESEARCH

A clear distinction in the often interchangeably used terms 'Handling Qualities' and 'Flying Qualities', and their respective requirements is provided in ESDU 92006<sup>[5]</sup>:

### *Handling Qualities*

The parameters that characterise the stability, control, and response of an aircraft and so govern the ease and precision with which a pilot is able to fly an aircraft.

### *Handling Qualities Criteria*

The identification and quantification of the parameters which characterise the handling qualities.

### *Flying Qualities*

The pilot assessment of how well one is able to fly an aircraft to complete a range of tasks required and is wholly subjective.

### *Flying Qualities Requirements*

The statutory regulations to which the aircraft must conform in order to be certified to fly, outlined by the States' aviation governing body.

Extensive research, flight experience, and experimentation into this field led to the development of design specifications and recommendations used internationally in the aircraft design process:

- Flying Qualities of Piloted Airplanes – MIL-F-8785C and MIL-HDBK-1797<sup>[6]</sup>
- Handling Qualities Requirements for Military Rotorcraft – ADS-33E-PRF<sup>[7]</sup>
- Design and Airworthiness Requirements for Service Aircraft – Def.Stan.00-970<sup>[8]</sup>

The criteria for established aircraft configurations are broken down into longitudinal and lateral dynamics and their respective dynamic modes; the longitudinal dynamics are described by second order short period and long period (Phugoid) oscillations and the

lateral dynamics by two first order modes, roll subsidence and spiral, and a second order Dutch roll oscillation. Typical design parameters can include response time delays, stick displacements, stick forces, overshoot, initial and steady state accelerations. The aircraft design aim is to have stable dynamic modes with minimal inter-axis coupling between the longitudinal and lateral dynamics.

In manned operations, aircraft are assessed both quantitatively and qualitatively in their ability to complete role-relevant tasks. These tasks are referred to as Mission Task Elements (MTEs) and are designed to expose any deficiencies in the aircraft dynamic response by evaluating the 'average' pilot's workload to achieve the required task performance. The Cooper-Harper Handling Qualities Rating Scale<sup>[9]</sup> is a descriptive decision-making chart which has been developed to quantify pilot opinion and associated level of flying qualities defined in Table 1.

Table 1 - Flying Qualities Levels<sup>[5]</sup>

LEVEL	DESCRIPTION
1	Task achieved without excessive pilot workload.
2	Some degradation in task effectiveness, or increase in pilot workload or both.
3	Aircraft can be controlled but with severe task degradation. The total workload of the pilot is approaching the limit of his/her capacity.

## 2.1 UAS Flying Qualities

Holmberg et al. present a succinct introduction to the application of current manned Flying Qualities Requirements to UAS, noting several deficiencies in the application of current standards and opportunities for research.<sup>[10]</sup> The first deficiency highlighted is the limited number of aircraft classes currently defined and into which many UAS do not fit. Considerations such as airframe expendability, mission performance objectives and integration into non-segregated airspace need to be addressed, especially for UAS with limited flight envelopes and built-in expendability. Alternative launch and recovery techniques such as catapults and nets also present new flight phases in need of clear requirements definition.

Another avenue for research are methods to qualitatively assess UAS flying qualities. Vehicle state tolerances for desired and adequate performance can be used in a similar manner to current manned requirements. However, variations caused by pilot factors such as experience, technique and perception are no longer applicable.

Despite this, by splitting the UAS into mission sensor and aircraft subsystems, UAS flying qualities can be thought of as being how well the UA enables the mission sensor to perform its function. Holmberg et al. note this is one area in which NAVAIR plans to conduct further research.

The remainder of Holmberg et al.'s paper explores the applicability of the detailed requirements for UAS flying qualities including static stability, fast and slow dynamic modes, control, take-off and landing, stalls, out-of-control flight and recovery. A summary of deficiencies in applicability is provided in Table 2.

Table 2 - Summary of Manned Flying Qualities Requirements deficiencies when applied to UAS<sup>[10]</sup>

STATIC STABILITY	Ensuring closed-loop static stability provides stability within the flight envelope. Slight instability in Level 3 or transonic flight is unacceptable for UAS as well as instability due to disturbance just outside of the flight envelope.
SLOW DYNAMICS	The phugoid damping requirements will likely differ from manned, particularly for speed and altitude holds, and failure modes. Spiral stability must exist for UAS with no pilot.
FAST DYNAMICS	Although ride quality and intuitive control may no longer be critical, the damping requirements may need to be increased for fine target tracking tasks. The mission sensors and their ability to handle large oscillations of the platform whilst achieving mission performance will likely dictate these requirements.
CONTROL	Pitch, roll and yaw control can be limited by aerodynamically available control power, flight control actuators, stability augmentation and stick/pedal force characteristics. Although the stick force characteristics and PIO requirements are not applicable, System Induced Oscillations (SIO) still remain a consideration, particularly in helicopter and ship airwake interactions. These include surface deflection and rate limits, phase and gain margins, and physical and computational latency. Similar to manned aircraft, UAS must have sufficient control margin to recover from all attainable angles of attack (AoA), stall, deep stall and spins. The application of PIO analysis to SIO is one opportunity for further research.
TAKE-OFF & LANDING	Requirements for the greater variety of launch and recovery techniques will need to be established. They will need to include pneumatic and rocket launched, cable, net and wire recoveries, belly landings, parachutes and landings on moving sea or land vehicles. Ship-borne operations are identified as a large area of research for all aircraft types.
STALLS, OOC FLIGHT, RECOVERY	This area requires in-depth high AoA dynamics analysis, robust control law design and available control margins. This may be incompatible with UAS for less sophisticated and cheap systems which are designed for basic stabilisation and navigation. There are opportunities for investigation in recovery algorithms, particularly for UAS that intend to be certified to fly in non-segregated airspace.

Holmberg et al. concludes that research efforts will be concentrated in:

1. Adapting piloted specifications to ensure mission performance while considering air vehicle and mission payload trade-offs;
2. Adapting piloted specifications for airworthiness;
3. MTEs and flight test manoeuvres; and
4. Departure resistance and upset recovery algorithms and techniques.

The project being reported in this paper aims to contribute to the research effort in areas 1, 2 and 3.

## 2.2 Maritime Operations Research

This Section provides a very brief overview of the literature relating to UAS ship-deck landings. It begins by covering different techniques used in UAS recovery before touching on work by two centres of Ship-Helicopter simulation at Pennsylvania State University and the University of Liverpool.

Garratt et al.'s work at the University of New South Wales explores the technologies in development to operate a small UAS, the Yamaha RMAX helicopter, from a ship.<sup>[11]</sup> One of the first hurdles to overcome to navigate to a ship is the relative position system needed to locate the ship deck. A 'classic' GPS system is subject to satellite availability, signal blockage and jamming, whilst radar navigation systems are expensive and emit large levels of radio frequency (RF) radiation. Two alternatives are a Shipboard Relative GPS (SRGPS) or the UAV Common Automatic Recovery System (UCARS) developed by Sierra Nevada Corporation which employs millimetre-wave radar as used on the Northrop Grumman Fire Scout and the Bell Eagle Eye.

Garratt et al. propose an alternative to these methods using a combination of a laser rangefinder, a downward optical sensor and a robust ship motion prediction algorithm to predict the quiescent periods to be used to land the vehicle. The laser uses a conical scanning pattern that builds an array of 3D co-ordinates of the ship deck plane, estimating its orientation for position tracking and relative altitude. The visual system uses a beacon located on the deck in conjunction with the laser to fix the UAS position relative to the deck centre and can successfully track from a range of 100m in bright sunshine. The ship motion prediction algorithm uses a second order function with parameters populated from a recursive least squares method allowing the ship motion to be predicted up to 5 seconds ahead.

There are a number of other visual tracking systems in development. Work at the University of Southern California makes use of a pattern-finding algorithm using identifiable polygons against the background of the deck.<sup>[12]</sup> The size and skew of these known polygon shapes allows the estimation and tracking of the deck orientation and position. A successful landing was demonstrated without deck motion. The US Naval Postgraduate School has devised an Infra-Red (IR) tracking system using heat signatures from the ship such as the smoke stack.<sup>[13]</sup> Three known ship hotspot positions allow the calculation of the azimuth and elevation of the ship relative to the helicopter. However, pure visual systems are subject to factors such as ship motion and sea spray which carry the risk of obscuring part or all of these tracked items from the camera's limited field of view.

Research at Pennsylvania State University over the last decade has focused on the development of gust-rejection control laws for ship-borne helicopter operations. Early work conducted by Horn and Bridges proposed an optimised model-following PID SAS with an airwake compensator (AWC) loop designed using the spectral properties of the ship air wake.<sup>[14]</sup> The control implementation reduced the helicopter rotational motion in all states but was particularly effective at reducing roll. The AWC scheme was limited as it had to be generated offline. It was also computationally expensive in that each aircraft, ship and wind combination would have to be individually designed.

Later papers published by Cooper et al.<sup>[15][16]</sup> removed some of the limitations of this process by generating the compensation scheme 'online'; whilst operating in the ship-borne environment without prior knowledge of the ship's airwake properties. The online process is, however, still quite computationally expensive, requiring a dedicated processor separate from the remainder of the control architecture with an updated compensation scheme generated every 4 seconds. Real-time simulation trials found the compensator improved pilot handling qualities ratings by an average of 2 ratings on the Cooper-Harper Handling Qualities Rating Scale and was particularly effective in higher wind conditions. Reduced pilot control activity and increased aircraft response predictability were cited as the reasons for the improvement.

The UoL has similarly been involved in ship-helicopter research particularly in the continued improvement of flight simulation fidelity and the helicopter-ship dynamic interface. A high-fidelity simulation environment has been established by incorporating a time-accurate CFD airwake in the full motion flight simulators HELIFLIGHT and HELIFLIGHT-R.<sup>[3][17][18][19]</sup>

Recent work by Scott et al. looks at the effect of ship scale on the airwake and the subsequent forces and moments acting on a SH-60B around the ship deck.<sup>[20]</sup> The larger scale ships were found to create larger vortical structures containing increased turbulent energy and of a size comparable to the helicopter rotor disk. The increased forces and moments experienced by the aircraft in the larger ship airwake were used to predict erosion of the control and power margins.

These papers serve to highlight both the complexity of the ship airwake environment and the importance of accurate sensors in compensating for turbulence and tracking the ship deck. Sensor and actuator accuracy and dynamics are therefore expected to be key factors in meeting FQRs to be established by this body of research. The erosion of control and power margins in a larger ship airwake gives some indication of the effect of aircraft scale in relation to the airwake and is expected to be addressed in later stages of this research project.

### 3. UDM CONFIGURATION

The UAS Dynamics Model (UDM) used in this study builds on work conducted by Schöenberg at the German Aerospace Centre (DLR) investigating side stick handling qualities.<sup>[21]</sup> Schöenberg's paper outlines the formation of a Helicopter model built around the inversion of Rotorcraft HQRs defined in ADS-33E-PRF. The model is fundamentally non-physical in that the aircraft dynamics are described by a configurable set of transfer functions. These transfer functions describe the total response of all of the individual system components (e.g. actuators, sensors, FCS). The translational dynamics are based on standard rigid-body dynamics and use a 'lifting' force acting along the normal aircraft body axis which, when tilted, drives translational accelerations.

The UDM has been developed from this work and is designed to be highly reconfigurable with minimal complexity. The simple model structure is desirable to enable rapid modification of the parameters that define the system dynamics. A benefit of using this technique will be the relative simplicity of relating model parameters back to ADS-33E-PRF enabling the formation of UAS-specific FQRs as part of this investigation.

Two basic rotational response types, Rate Command (RC) and Attitude Command (AC), are defined as first order and second order transfer functions respectively, with additional command types, such as Translation Rate Command (TRC), defined as outer control loops. Additional model complexity can be added around the core model

functions to explore saturation limits, sensor errors, system delays and dynamics of individual components as required. Figure 1 illustrates the top level of the UDM structure and shows the process flow of the control and state signals. The remainder of this Section describes the core model functions and presents example outputs of the RC, AC and TRC response types which are the fundamental response types described in ADS-33E-PRF.

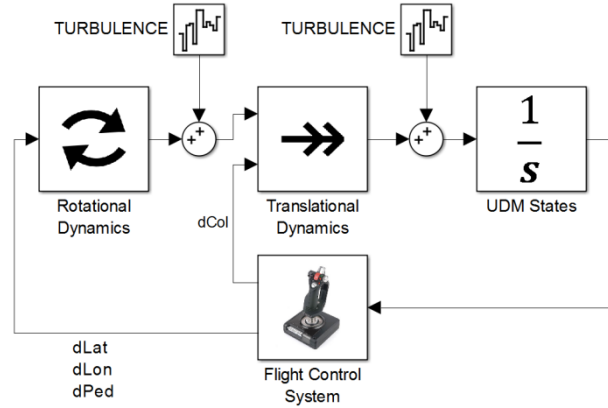


Figure 1 - Top level structure of UDM

#### 3.1 Rotational Dynamics

Rate Command responses are defined in each of the classical aircraft control senses: pitch, roll and yaw. Heave rate is modelled as part of the translational dynamics described in Section 3.2, whilst unconventional control channels in surge and sway are outside the initial scope of this investigation. Inter-axis coupling is also not included at this stage but will be included during the investigation as coupled dynamics are common to most rotorcraft configurations. This approach leads to an ideal system with individual control in each channel and serves to give some early model simplicity when sweeping a large number of model parameters.

The RC response type is modelled as a first order transfer function containing a single time constant parameter  $\tau$  which controls the system settling time. A step input for this response type will hold a fixed rotational rate once settled and similarly, once the command input is removed, the rate returns to zero and holds the final attitude achieved. Equation 1 illustrates the transfer function form used in the pitch axis channel:

$$\frac{q}{q_{cmd}} = \frac{1}{\tau_{LON}s + 1} \quad (1)$$

The outputs from the rotational rates can then be converted into Euler angles by converting from the

body axis to earth axis system and then integrating equations 2, 3 and 4 respectively:

$$\dot{\phi} = p + q \sin \phi \tan \theta + r \cos \phi \tan \theta \quad (2)$$

$$\dot{\theta} = q \cos \phi - r \cos \phi \quad (3)$$

$$\dot{\psi} = q \sec \theta \sin \phi + r \sec \theta \cos \phi \quad (4)$$

The AC response type is modelled as a second order transfer function with natural frequency and damping parameters which control the frequency, overshoot and settling time of the system response. A step input to this response type will hold a fixed attitude once settled. The attitude command response is applied to the rotational axes with equation 5 describing the transfer function form used in the roll axis:

$$\frac{\phi}{\phi_{cmd}} = \frac{1}{s^2 + 2\zeta_{LAT}\omega_{LAT}s + \omega_{LAT}^2} \quad (5)$$

The Euler output from this transfer function must be differentiated and converted to the body axis system to find the rate using equations 6, 7 and 8:

$$p = \dot{\phi} - \dot{\psi} \sin \theta \quad (6)$$

$$q = \dot{\theta} \cos \phi + \dot{\psi} \cos \theta \sin \phi \quad (7)$$

$$r = -\dot{\theta} \sin \phi + \dot{\psi} \cos \phi \cos \theta \quad (8)$$

### 3.2 Translational Dynamics

The translational dynamics are modelled in the body axis frame using the following equations of motion:

$$\dot{u} = vr - wq - g \sin \theta + X_u u \quad (9)$$

$$\dot{v} = wp - ur + g \cos \theta \sin \phi + Y_v v \quad (10)$$

$$\dot{w} = uq - vp + g \cos \theta \cos \phi + Z_{\delta COL} \delta_{COL} + Z_w w \quad (11)$$

The accelerative response of the aircraft is defined by the damping derivatives  $X_u$ ,  $Y_v$  and  $Z_w$  along the three translational axes. The final parameter is the heave response derivative  $Z_{\delta COL}$  which is used to define the control power after 1.5 seconds in the vertical rate response.<sup>[21]</sup> These parameters can be modified to represent the characteristics of different UAS in terms of size, configuration and available power.

The remaining aircraft states can be found using the directional cosine matrix to convert between body axis and earth axis systems and integration to find inertial velocities and position.

### 3.3 Comparison of Responses to a Step Input

Figure 2 illustrates the pitch axis responses in pitch rate, pitch attitude and longitudinal body velocity in RC and AC modes. A TRC response, that is directly controlling a translational velocity in the aircraft body axis, is included to demonstrate the application of an outer control loop. Figure 3 and Figure 4 demonstrate the model configurability by modifying the RC and AC parameters in the pitch axis response.

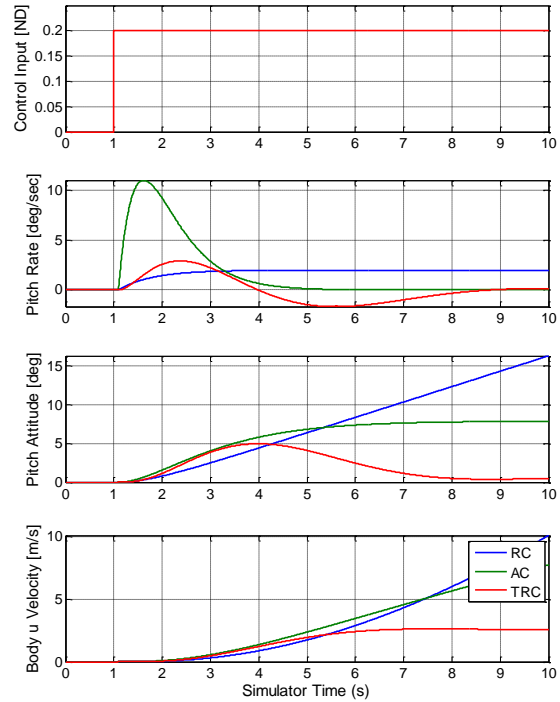


Figure 2 - RC, AC and TRC Response to step control input

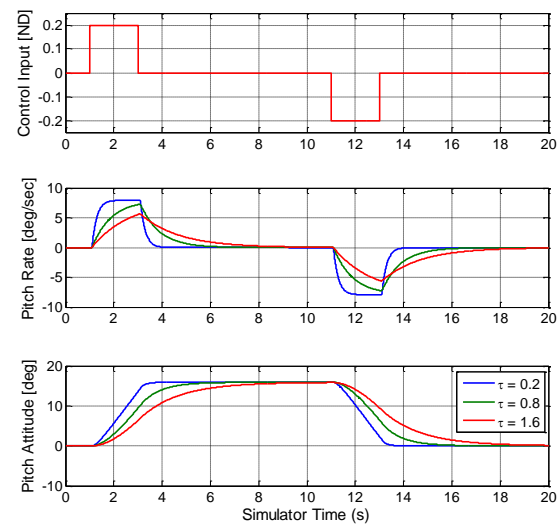


Figure 3 – RC Response to changing time constant,  $\tau$

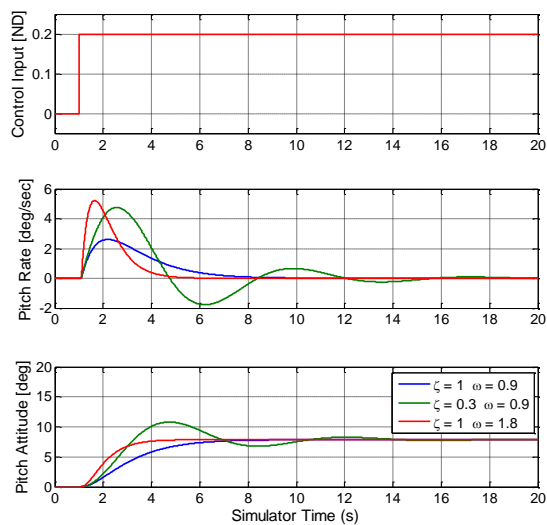


Figure 4 - AC Response to changing damping,  $\zeta$ , and natural frequency,  $\omega$

#### 4. MISSION TASK ELEMENTS (MTEs)

One of the fundamental tenets of manned aircraft flying qualities analysis is the definition of Mission Task Elements. They provide a means by which a pilot-vehicle system can be assessed when attempting to perform a particular task. As such, it was considered essential for this investigation to define a set of UAS-relevant naval launch and recovery MTEs. Manned launch and recovery manoeuvres used in helicopter-ship deck operations by the Dutch and UK navies can be broken down into the following steps<sup>[22]</sup> (see Figure 5):

##### Approach & Landing:

1. Approach the ship to 'Hover Wait' position alongside the ship with the helicopter's longitudinal axis parallel to the ship's centre line.
2. Translate the aircraft laterally to the hover position over the landing spot.
3. Descend towards the ship deck and land.

##### Take-off:

1. Align the helicopter to the ship's centreline, with the nose in line with the sailing direction.
2. Hover above the deck in line with the ship's heading.
3. Translate the aircraft laterally to the hover position alongside the ship.
4. Turn away 30° from the ship's heading and climb away.

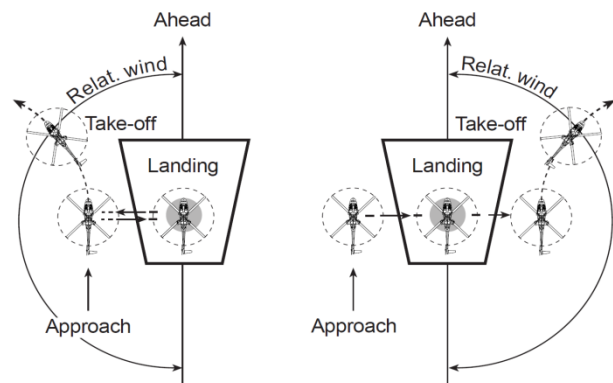


Figure 5 - Fore/Aft Landing and Departure Manoeuvres for the full range of WOD Conditions<sup>[18]</sup>

One of the key features of naval launch and recovery operation is the presence of the ship airwake. This is covered in more detail in Section 5 but the presence of this wake had to be taken into account when developing the MTEs.

Using the manoeuvres of Figure 5 as a basis, the vehicle movements were abstracted to become tasks into and within a volume of turbulent air flow. A series of MTEs have been identified as:

1. Transition into/out of turbulence;
2. Reposition in turbulence;
3. Hover (station keeping in turbulence) and
4. Landing (in turbulence).

Existing performance criteria deemed applicable to the MTEs have been drawn from ADS-33E-PRF. However, the performance requirements must ultimately be dictated by the aircraft role and operating environment, for this work the UK Royal Navy Type 23 Frigate. Setting appropriate performance boundaries is fundamental in establishing realistic FQRs for Maritime UAS operations. For example, if the boundaries are too strict, there is a risk the FQRs in the form of FCS Design Criteria become impractical both in terms of cost and possible instrumentation accuracy to implement on real hardware. The performance requirements will therefore be continually reviewed throughout the project with particular interest in the effects of aircraft size on the boundaries as the additional aircraft are modelled.

The remainder of this Section will now describe the MTEs in more detail. As discussed above, the current quoted task tolerances should be considered to be preliminary only.

#### 4.1 Transition into/out of Turbulence

Starting on a 3° glide slope with a trimmed forward speed of 100 knots, the UDM decelerates into one side of the turbulent volume, matching ambient wind

speed and volume heading at an altitude of 25ft (Figure 6). The course contains a fixed turbulent volume tracked by the UDM at a height of 25ft above the sea. The distribution of turbulence within the volume is defined for each WOD condition.

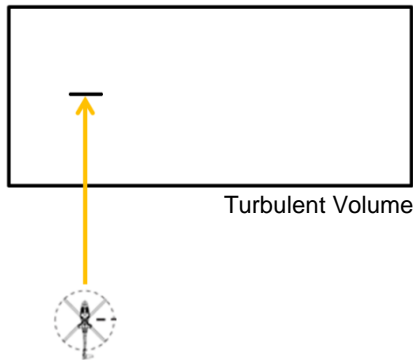


Figure 6 - Transition into/out of Turbulence

The MTE aims to assess the UDM's ability to:

1. Perform precision glide slope tracking;
2. Precisely control airspeed whilst performing a deceleration and descending on the glide slope.

PERFORMANCE REQUIREMENTS	DESIRED	ADEQUATE
Maintain Glide Slope ( $\pm X$ ft)	5	10
Maintain Final Height ( $\pm X$ ft)	2.5	5
Maintain Final Airspeed ( $\pm X$ kts)	2.5	5
Maintain Heading ( $\pm X^\circ$ )	5	10
Establish a Stabilised Hover within (s)	10	10

#### 4.2 Reposition in Turbulence

This manoeuvre starts with the UDM in a hover, trimmed to ambient conditions on one side of the turbulent volume, matching the volume heading at an altitude of 25ft. The UDM must laterally reposition to a stabilised hover over the target landing area (Figure 7).

The MTE aims to assess the UDM's ability to:

1. Maintain longitudinal position, heading and altitude whilst repositioning in spatially varying turbulence, and
2. Transition from translating flight into a stabilised hover maintaining precise position, heading and altitude in spatially varying turbulence.

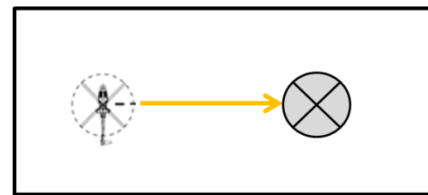


Figure 7 - Reposition in Turbulence

PERFORMANCE REQUIREMENTS	DESIRED	ADEQUATE
Maintain Longitudinal Position ( $\pm X$ ft)	2.5	5
Maintain Heading ( $\pm X^\circ$ )	5	10
Maintain Altitude ( $\pm X$ ft)	2.5	5
Maintain Hover Lateral Position ( $\pm X$ ft)	2.5	5
Establish a Stabilised Hover within (s)	10	10

#### 4.3 Hover

This manoeuvre starts with the UDM in a hover trimmed to ambient conditions over the landing area, matching the volume heading at an altitude of 25ft. The UDM must track the prescribed landing area.

The MTE aims to assess the UDM's ability to:

1. Precisely control position and heading prior to the final descent to the landing point in turbulence.

PERFORMANCE STANDARDS	DESIRED	ADEQUATE
Maintain Longitudinal and Lateral Position ( $\pm X$ ft)	2.5	5
Maintain Heading ( $\pm X^\circ$ )	5	10
Maintain Altitude ( $\pm X$ ft)	2.5	5
Maintain Stabilised Hover (s)	30	30

#### 4.4 Landing

This manoeuvre starts with the UDM in a hover trimmed to ambient conditions over the landing area, matching the volume heading at an altitude of 25ft. The UDM must track and descend to the prescribed landing area.

The MTE aims to assess the UDM's ability to:



1. Precisely control position and heading during the final descent to the landing point in spatially varying turbulence.
2. Control descent rate to land during a quiescent period in the ship's motion.

PERFORMANCE STANDARDS	DESIRED	ADEQUATE
Maintain Longitudinal and Lateral Position ( $\pm X$ ft)	2.5	5
Maintain Heading ( $\pm X^\circ$ )	5	10
Within Quiescent Period	YES	YES

## 5. STOCHASTIC TURBULENCE MODELS

Stochastic Turbulence models have long been used in simulation. One such method, named after Theodore von Karman, uses Power Spectral Density (PSD) characteristics to model wind gusts as linear and angular velocity components.<sup>[23]</sup> The wind speed perturbations are generated by passing a white-noise signal through a filter which approximates the frequency content characterised in the PSD. As stochastic methods are non-deterministic in nature, unique turbulence is generated in each simulation. This overcomes the inherent limitations in using an airwake generated with Computational Fluid Dynamics (CFD) which is limited in duration due to the large computational cost required to create it.<sup>[3]</sup> By characterising the CFD wake using a PSD however, the stochastic method retains the spectral properties of the wake without the need to loop the data to allow for extended simulation runs.

Building on stochastic techniques, two potential turbulence methods are to be explored during this research; the Control Equivalent Turbulence Inputs (CETI) method<sup>[24]</sup> and the Virtual AirDyn<sup>[25]</sup> method. The CETI model uses flight test data and a pseudo-inverse aircraft model to extract aircraft motion due to turbulence as control inputs. The Virtual AirDyn model resolves forces and moments acting on the aircraft, which is immersed in the ship's airwake, at fixed points around the landing deck, and which are then converted into rotational and translational accelerations.

The turbulence examples presented in this paper use an unsteady CFD-generated airwake over a Type 23 Frigate geometry that was created using Detached Eddy Simulation (DES) techniques at a time step of 0.0125 seconds.<sup>[3]</sup> The airwake data is down-sampled to 20Hz for use in the FLIGHTLAB modelling environment. Previous piloted flight trials using a SH-60B-like helicopter model have been conducted in the UoL's HELIFLIGHT-R 6-DOF Motion Flight Simulator where pilots were asked to

perform a series of deck landings in a full range of WOD and ship motion conditions.

The flight trial data, down-sized DES airwakes and the FLIGHTLAB SH-60B Helicopter model have all been used to populate the UDM, CETI and Virtual AirDyn Turbulence models. The remainder of this Section describes the CETI and Virtual AirDyn models in more detail.

### 5.1 CETI TURBULENCE MODEL

The CETI approach was first employed by the National Research Council (NRC) Canada on a Bell 205 helicopter.<sup>[26]</sup> This technique has been replicated by Lusardi et al. using a UH60 model and validated in flight tests<sup>[27][28]</sup>, later by DLR<sup>[20]</sup> using an EC135.

The process relies on a combination of recorded flight test data and a 9-state linearised aircraft model to find the residual dynamic motions caused by turbulence. With both the aircraft states and pilot inputs known, the state space equations (Eq.12) can be rearranged using a pseudo-inverse (least-squares solution) control matrix to find the equivalent control input driven by the turbulence (Eq.13) (Figure 8).

$$\dot{x} = Ax + Bu \quad (12)$$

$$u_{Turb} = B^{-1}(\dot{x} - Ax) - u_{Input} \quad (13)$$

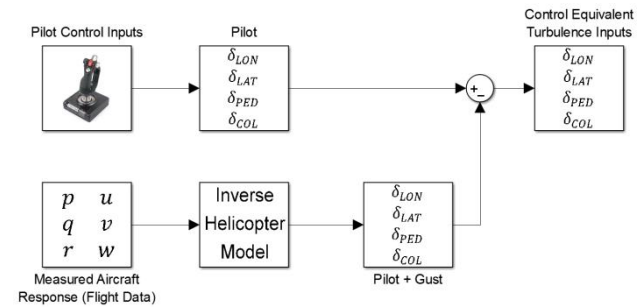


Figure 8 – CETI extraction using inverse modelling

The CETI time-history signals are used to generate PSDs in the frequency domain for each control channel. A transfer function of the form given in Equation 14 is fitted in MATLAB using a least-squares method.

$$H(s) = 4A\sqrt{\beta} \frac{[1 + B(\beta s) + C(\beta s)^2]}{[1 + D(\beta s) + E(\beta s)^2 + F(\beta s)^3]} \quad (14)$$

$$\beta = \frac{L}{V} \quad (15)$$

The coefficients A-F are scalars based on the least-squares fitting of the spectra and  $\beta$  is a function of L, the measure of the correlation length of the unsteady loads and V, the free-stream velocity.<sup>[3]</sup>

The turbulence is integrated into the UDM by feeding white noise into the parameterised transfer function (Eq. 14). The CETI signal is then fed into a first order transfer function describing the dynamics of the un-augmented baseline aircraft and summed with the UDM aircraft states (Figure 9).

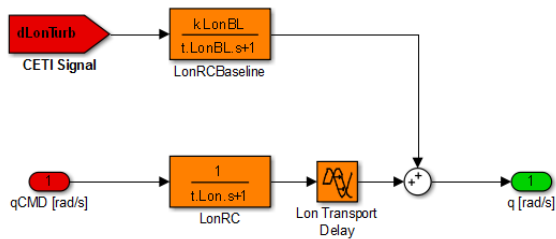


Figure 9 - CETI Turbulence added to Pitch Channel

An example CETI time history generated from a flight trial for a Green 45° (winds from the starboard side) 45kt WOD condition is shown for each control volume in Figure 10.

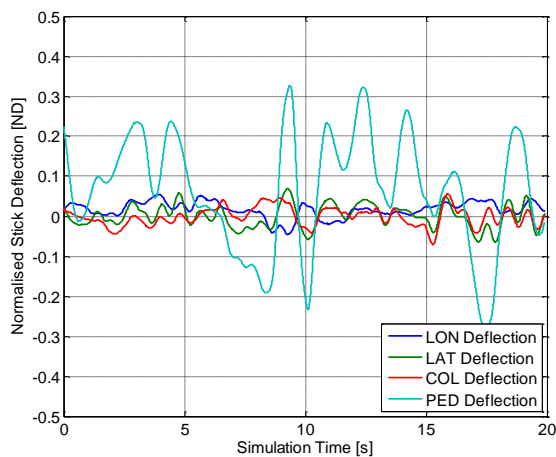


Figure 10 - Normalised CETI for 45kts G45° WOD condition

## 5.2 VIRTUAL AIRDYN TURBULENCE

The Virtual AirDyn builds on techniques developed at the UoL<sup>[3][25]</sup> to quantify the unsteady forces and moments imposed on an aircraft by a ship's airwake during a deck landing. The method uses the SH-60B Helicopter modelled in FLIGHTLAB and held stationary in space at multiple points around the ship deck while immersed in a time-accurate airwake. The unsteady forces and moments are measured at Airload Computation Points (ACPs) shown in Figure 11 and resolved at the aircraft centre of gravity.

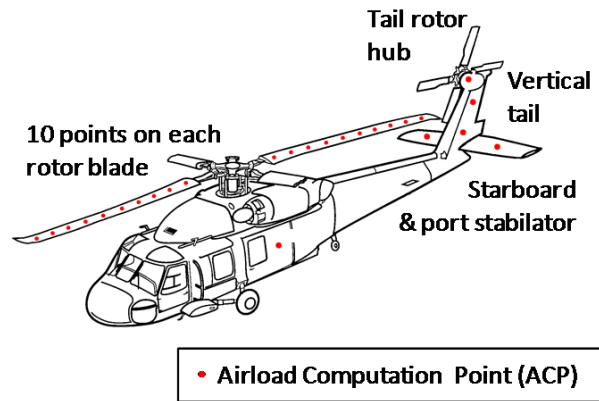


Figure 11 - SH-60B model with ACPs

The forces and moments are converted into translational and angular accelerations using the known aircraft mass and inertias before PSDs are generated. Unlike the CETI model, the turbulence is modelled in all 6 aircraft DOF (3 linear, 3 rotational). As multiple points around the deck are measured, the effective resolution of the turbulence model is higher than the CETI model. This comes at the cost of added model complexity by scheduling these parameters as the UDM moves around the turbulent environment. Unlike the CETI model, the accelerations can be applied directly to the aircraft states as shown in the top level UDM structure (Figure 1).

Example moments from a mid-deck position are shown in Figure 12.

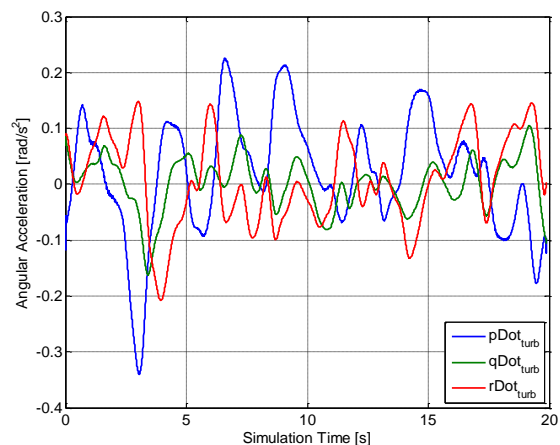


Figure 12 - Moments in Pitch, Roll and Yaw for 45kts G45° WOD condition

A brief summary of each turbulence model's advantages and disadvantages are provided in Table 3.

A research question to be answered by exploring these two methods is therefore whether there is a significant difference in the predicted FCS Design Limits arrived at by changing the level of detail

captured using both of these approaches. The next phase of work should begin to address this question.

Table 3 - CETI and Virtual AirDyn Advantages and Disadvantages

CETI	VIRTUAL AIRDYN MODEL
<ul style="list-style-type: none"> <li>+ Captures control limitation effects (e.g. Loss of Tail Rotor Effectiveness LTRE)</li> <li>+ Simple model</li> <li>+ Ability to directly implement on hardware</li> <li>- Dependent on flight test data</li> <li>- Requires validated linear model</li> <li>- Only 4 DOF turbulence</li> <li>- Captures turbulence of the general area</li> </ul>	<ul style="list-style-type: none"> <li>+ Captures 6 DOF turbulence</li> <li>+ Captures finer detail in the wake</li> <li>+ Not dependent on flight test data</li> <li>- More complex model</li> <li>- Requires validated non-linear model</li> <li>- Requires validated airwake</li> </ul>

## 6. CONCLUDING REMARKS

A highly configurable UAS Dynamics Model environment has been developed with RC, AC and TRC response types demonstrated. MTEs describing typical ship-deck operations have also been established based on ADS-33E-PRF requirements and the operating environment around the Type 23 Frigate.

Two stochastic turbulence modelling schemes, CETI and Virtual AirDyn, have been generated based on flight tests and techniques in the FLIGHTLAB modelling environment and incorporated into the UDM model structure.

Future work will begin to assess the UDM performing the Maritime MTEs in the G45° WOD condition. FQR boundaries will be generated by modifying the UDM response types and assessing the UDM performance against the MTE performance criteria. The results of this investigative stage will then be validated using a non-linear modelling environment before expanding the test matrix to explore the effects of aircraft size and configuration.

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