

PROGRESS IN ESTABLISHING SCALABLE FLYING QUALITIES REQUIREMENTS FOR MARITIME UNMANNED ROTORCRAFT SYSTEMS

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ABSTRACT

In recent years, there has been considerable effort to understand the flying environment around landing decks on naval vessels ⁽¹⁾. The airwake generated in the lee of the ship's superstructure contains complex unsteady shear layers and vortical flow features and is one of the primary limiting factors in manned Ship-Helicopter Operating Limits (SHOLs). The magnitude, frequency content and dimensions of these flow features are all expected to have a significant effect on the required dynamics and control margins of the rotorcraft control system architecture. The determination of Flying Qualities Requirements (FQRs) for Maritime Unmanned Aircraft Systems (UAS) is therefore important for the future procurement of UAS intended to operate in this environment. The proposed paper will report on results in capturing accurate and scalable turbulence models as part of a Dstl-sponsored project at the University of Liverpool (UoL) which aims to address the research question:

"What are the key UAS flight control system (FCS) design criteria that will enable the safe and reliable operation of UAS from naval surface vessels?"

The paper will report on the results of simulations conducted using the tools developed to predict the flying qualities boundaries for a successful recovery of a SH-60 'like' helicopter operating from a UK Type 45 'like' destroyer. The tools include a linear UAS Dynamics Model (UDM), Stochastic Airwake Turbulence model and recovery Mission Task Elements (MTE) ⁽²⁾. The UDM is a linear model simulation which uses ADS-33E-PRF based parameters to describe aircraft system dynamics ⁽³⁾ ⁽⁴⁾. Sweeps of these parameters which include rise times, time constants, natural frequencies, damping ratios and time delays are used to evaluate how aircraft performance degrades with changing aircraft dynamics whilst operating in this unsteady environment.

At present, ADS-33E-PRF provides limited guidance on disturbance rejection characteristics. Recent work by the U.S. Aeroflightdynamics Directorate (AFDD) ⁽⁵⁾ proposes improvements to this issue by defining specifications based on Disturbance Rejection Bandwidth (DRB) for each control loop in a position hold type control system (Table 1); Attitude Command Attitude Hold (ACAH), Translational Rate Command (TRC) and Position Hold (PH). The DRB for each loop can be found by breaking each control loop between the disturbance and its response (Figure 1). The resulting transfer function

(Equation 1), also known as the sensitivity function, provides a frequency domain plot where disturbances above -3dB frequency will not be satisfactorily rejected by the control loop. The -3dB point represents an attenuation factor of 0.5 on the disturbance magnitude passed directly to the aircraft. A similar limit is also placed on the Disturbance Rejection Peak (DRP) given by the maximum magnitude.

Table 1 - Disturbance Rejection Bandwidth & Peak Criteria

CONTROL LOOP	DRB (rad/s)	DRP (dB)
Attitude (ACAH) <i>Pitch</i> <i>Roll</i> <i>Yaw</i>	> 0.5 > 0.9 > 0.7	< 5
Translational (TRC) <i>Longitudinal</i> <i>Lateral</i> <i>Vertical</i>	> 0.34 > 0.54 > 1.00	< 5
Position (PH)	> 0.17	< 3

$$\frac{y(s)}{\delta_g(s)} = \frac{1}{1+G(s)C(s)H(s)} \tag{1}$$

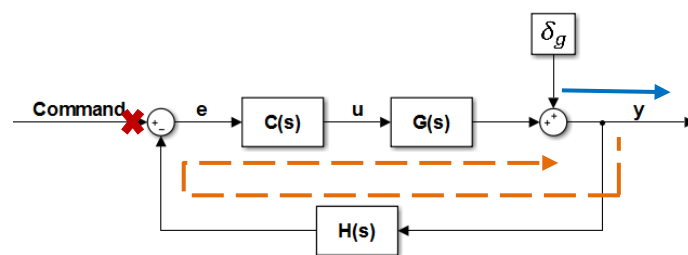


Figure 1 - General Feedback Control Loop showing DRB Loop

This paper will report on the applicability of these proposed specifications applied to the SH-60/Type 45 scenario by sweeping the parameters of the UDM from the inner loops to the outer loops in each control axes. For the inner-most loop, the ACAH loop, the plant is approximated by a second order low order equivalent system with phase delay (Equation 2). The natural frequency, damping and phase delay parameters of the inner loop dynamics map directly onto, for example, the existing ADS-33E-PRF roll bandwidth criteria (Figure 2)⁽³⁾. The roll bandwidth is defined as the lower of the two

frequencies given by gain-limited (grey lines) or phase-limited bandwidth (orange lines). Each line on these charts corresponds to increments of 0.5rad/s in natural frequency from 0.5rad/s to 4.5rad/s. An example of how these criteria are calculated for a Level-1 ACAH case (green circle) has been provided below with corresponding DRB limits. The dynamic system has a natural frequency of 3rad/s with critical damping. Using the ADS-33E-PRF specifications and DRB recommendations, the system has Level 1 Flying Qualities with disturbance rejection characteristics that exceed the minimum criteria.

$$G(s) = \frac{\omega_{\phi}^2}{s^2 + 2\zeta\omega_{\phi}s + \omega_{\phi}^2} e^{-\tau s} \quad (2)$$

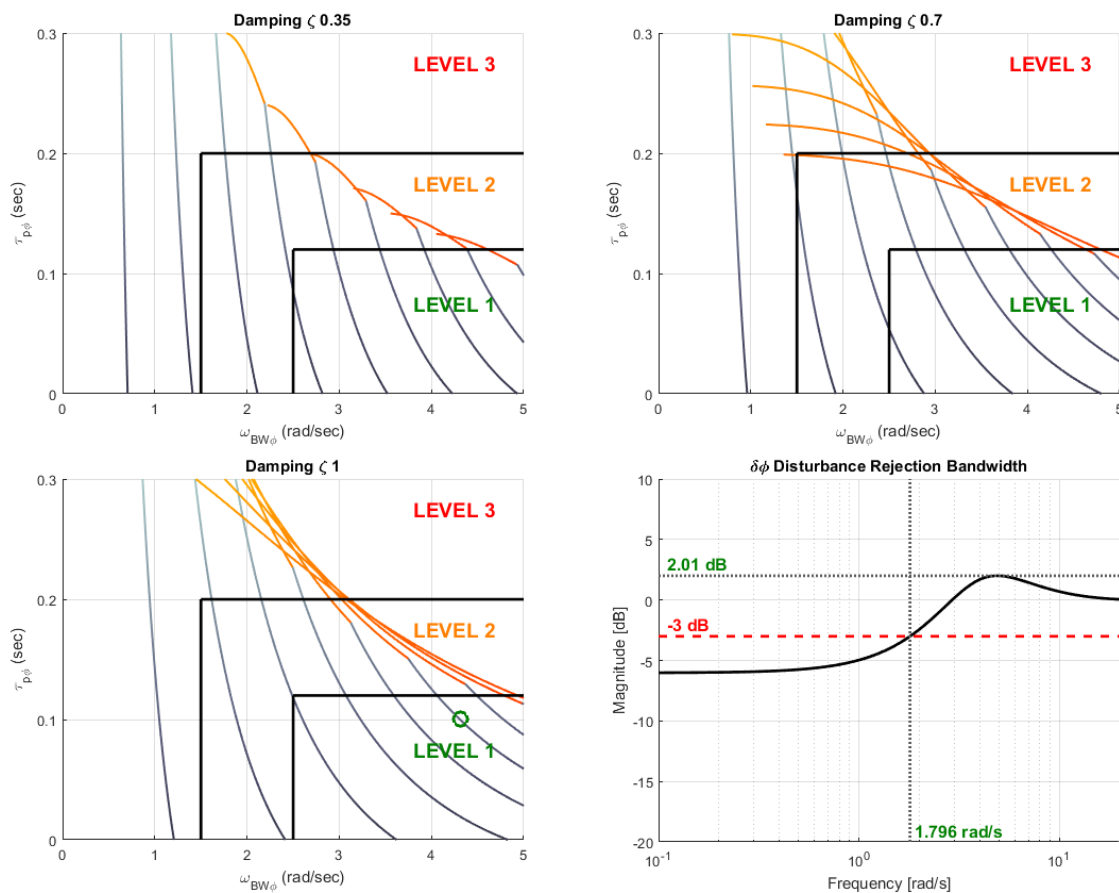


Figure 2 - ADS-33E-PRF Roll Bandwidth Target & Acquisition and example DRB chart

The paper will also report on progress made in capturing the turbulence experienced by aircraft operating in a ship airwake as a stochastic process. Using a high-fidelity simulation environment that has been built using FLIGHTLAB and SIMULINK, large time-accurate CFD airwakes have been incorporated into non-linear Flight Dynamics Models of a SH-60 ‘like’ helicopter to measure aircraft

disturbances as Forces and Moments in a process called the Virtual AirDyn⁽⁶⁾. Recent work has seen the expansion of the frequency and spatial content used by this technique for the development of higher fidelity Stochastic Turbulence models. Improvements have seen the length of time data increased from 30 seconds to 90 seconds, the sampling rate increased from 25Hz to 100Hz and the spatial resolution increased from 1m to 0.5m for the same volume over the ship deck. This represents a 50 fold increase in raw data size integrated into a real-time simulation capability. A sensitivity study of the ‘low’ resolution and ‘high’ resolution datasets will be presented and the impact of the additional lower frequency perturbations on the model explored.

This increase in resolution is of particular interest as the project aims to explore the effects of the airwake on smaller UAS. Previous reported work has shown decreasing aircraft size has a detrimental effect on control power requirements to overcome the same turbulent airwake^{(7) (8)}. Initial efforts to capture these changes in magnitude and frequency of disturbance has led to the development of spectral filters using a Dryden form (Equation 3 & Table 2). Figure 3 compares the Virtual AirDyn turbulence (blue line), the identified spectral filter (orange line) and the turbulence in the UDM (yellow line). A time domain representation of the normal velocity perturbation shows good agreement with the original Virtual AirDyn turbulence signal.

Finally, this paper will present a first pass in capturing how the spectral filters scale with aircraft size and ambient wind velocity by modifying the scaling factors of σ (standard deviation) and K (cut-off frequency).

$$H(s) = \sigma_{\delta} \frac{K_{\delta}^2}{(s + K_{\delta})^2} \quad (3)$$

Table 2 - Stochastic Turbulence Parameters (Dryden Form)

TURBULENCE PARAMETER	STANDARD DEVIATION	FILTER
δU	0.2202 ft/s	$0.2202 \frac{1.01^2}{(s + 1.01)^2}$
δW	1.1508 ft/s	$1.1508 \frac{1.55^2}{(s + 1.55)^2}$
δQ	0.0039 rad/s	$0.0039 \frac{0.98^2}{(s + 0.98)^2}$

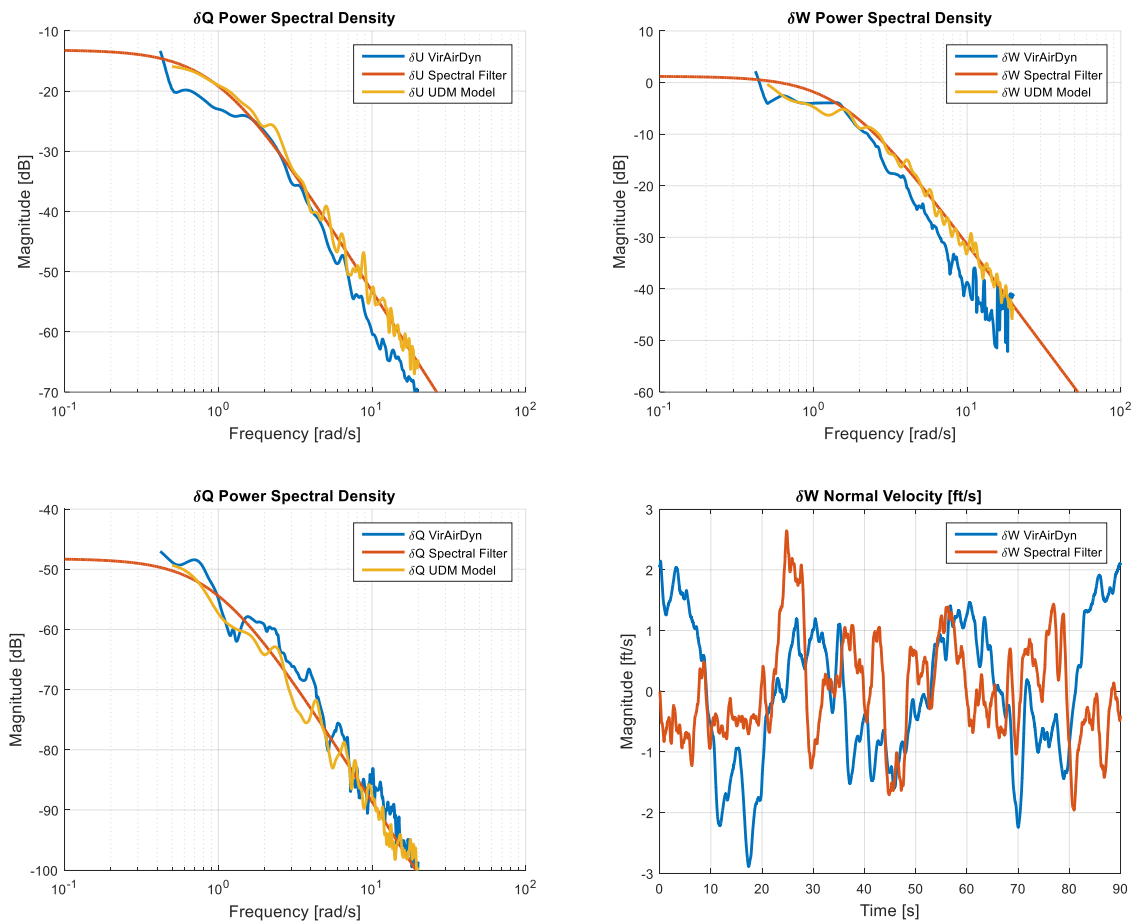


Figure 3 - Turbulence PSD and Time-domain Validation

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