

Piloted Evaluation of a UH-60 Mixer Equivalent Turbulence Simulation Model

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Abstract

A simulation study of a recently developed hover/low speed Mixer Equivalent Turbulence Simulation (METS) model for the UH-60 Black Hawk helicopter was conducted in the NASA Ames Research Center Vertical Motion Simulator (VMS). The experiment was a continuation of previous work to develop a simple, but validated, turbulence model for hovering rotorcraft. To validate the METS model, two experienced test pilots replicated precision hover tasks that had been conducted in an instrumented UH-60 helicopter in turbulence. Objective simulation data were collected for comparison with flight test data, and subjective data were collected that included handling qualities ratings and pilot comments for increasing levels of turbulence. Analyses of the simulation results show good analytic agreement between the METS model and flight test data, with favorable pilot perception of the simulated turbulence. Precision hover tasks were also repeated using the more complex rotating-frame SORBET (Simulation Of Rotor Blade Element Turbulence) model to generate turbulence. Comparisons of the empirically derived METS model with the theoretical SORBET model show good agreement providing validation of the more complex blade element method of simulating turbulence.

Introduction

Some of the most difficult helicopter flight conditions to simulate reliably are low speed/hover tasks in near earth turbulence. Methods of simulating the effects of turbulence on helicopters range from the straight forward approach of superimposing frozen-field turbulence velocity inputs at the vehicle center of gravity, as in fixed wing aircraft, to complex rotating frame turbulence models. While including turbulence velocities at the center of gravity has elicited favorable pilot comments at high speeds, as the aircraft speed is decreased, this type of turbulence has been criticized for its high frequency content and lack of variation. Improved pilot opinion of simulated hover/low speed turbulence has been achieved through the implementation of complex rotating frame turbulence models (Ref. 1). Models of this type however, are not well suited for use in control system design, a key area where turbulence modeling is needed. Another drawback of these models is that they can be difficult to implement in real-time simulations and, in general, have not been validated against flight.

To simulate the effects of atmospheric turbulence on a helicopter, the National Research Council (NRC), Canada derived environmental disturbance data from a record of their Bell 205 hovering in heavy turbulence (Ref. 2). The remnant angular rates and vertical accelerations were processed through a simple, first order inverse model of the aircraft. The resulting data traces, when used as inputs to the aircraft actuators, caused angular and vertical motion

similar to those measured in flight tests. The data traces were then scaled and filtered until the pilots agreed that the simulated turbulence felt subjectively like moderate turbulence in the Bell 205 aircraft. Using a similar approach and a higher order, on-axis inverse model of the UH-60 helicopter, Labows developed a simple, empirically based turbulence model for that helicopter (Ref. 3). The turbulence model used white-noise driven transfer functions that were scalable with wind speed and turbulence intensity, to generate equivalent turbulent lateral and longitudinal control inputs. These control inputs generated aircraft roll and pitch rates that had spectral characteristics that were comparable to the spectral characteristics of measured aircraft rates from flight in two levels of atmospheric turbulence.

The work in Ref. 3 has been expanded to develop a model that generates turbulent inputs to the directional and heave axes as well (Ref. 4). The process of extracting the aircraft actuator data traces due to turbulence has been improved through the use of a full inverse of an identified state-space hover/low-speed model of the UH-60 (Ref. 5). The white-noise driven transfer function based Mixer Equivalent Turbulence Simulation (METS) model that resulted, was developed to produce realistic hover/low speed turbulence effects for the UH-60 helicopter. The main objective of the current study was to validate the empirically derived METS model in a ground based piloted simulation and compare METS simulated turbulence with SORBET simulated turbulence.

Description of Experiment

To validate the METS model, a five-week piloted simulation study was conducted in the NASA Ames

Research Center Vertical Motion Simulator (VMS). The simulation utilized two experienced test pilots (pilot A and pilot B) to replicate the precision hover tasks that had been performed by a UH-60 helicopter during the development of the METS model. A description of the models used and the simulation facility follows.

METS model

The METS model is comprised of four simple white-noise driven transfer functions that generate equivalent disturbance inputs to the aircraft mixer. On the UH-60, the aircraft mixing unit is a mechanical device that combines, sums, and couples the cyclic, collective, and yaw inputs and provides proportional output signals to the main and tail rotor controls. The transfer functions were derived from flight test data collected on an instrumented UH-60 Black Hawk helicopter hovering in the turbulent flow field down wind of a large cube-shaped hangar. Two hover tasks were performed in these flight tests. The first hover task was conducted with the aircraft Stability Augmentation System (SAS) off, where the pilot was asked to maintain a loose position tolerance in both on- and off-axis orientations to the mean wind. Flight test data from this task were used to develop the METS model transfer functions listed in Table 1. The second hover task was conducted with the aircraft SAS on, where the pilot was asked to maintain a tight position tolerance in both on- and off-axis orientations. This task was replicated in the VMS during the simulation for comparison with data from flight.

Table 1. METS model transfer functions

Lateral and Longitudinal
$G_{\delta_g} = 0.278\sigma^{0.991} \sqrt{\frac{U_0}{\pi L} \left(\frac{1}{s + \alpha_w} \right)}$
Directional
$G_{\delta_g} = 0.501\sigma^{0.748} \sqrt{\frac{U_0}{\pi L} \left(\frac{1}{s + \alpha_w} \right)}$
Collective
$G_{\delta_g} = 0.068\sigma^{0.549} \sqrt{\frac{3U_0}{\pi L} \left(\frac{s + 10.2\alpha_w}{(s + 0.53\alpha_w)(s + 1.48\alpha_w)} \right)}$
$\alpha_w = \frac{2U_0}{L}$

The input parameters of the transfer functions listed in Table 1 are U_0 , the mean wind speed (ft/sec), σ , the vertical turbulence intensity (ft/sec), and L , the turbulence integral scale length which was set to 53.7 ft, the main rotor diameter of the UH-60 helicopter. A separate random number generator, each with a unique seed, generated the input signals for each the transfer functions. The random number generators' signals had a mean value of zero and a variance of 1 at a sample rate of 100 Hz. The outputs of the transfer functions were inches of mixer for

the respective controls. The METS model was implemented in the VMS aircraft math model by summing the outputs of the transfer functions with the pilot control and aircraft SAS signals as shown in Fig. 1.

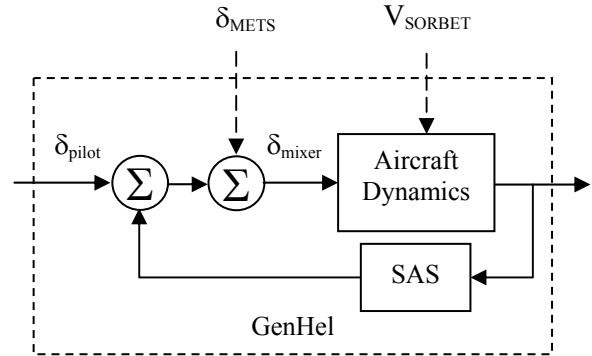


Fig. 1. METS and SORBET turbulence inputs to aircraft math model

Simulation Of Rotor Blade Element Turbulence (SORBET)

The turbulence model selected for comparison was the SORBET blade element turbulence model, which was already implemented and available in the VMS (Ref. 1). The METS and SORBET models share a common basis for generating disturbances, the Dryden spectral turbulence models, but differ in the method of injecting the disturbances into the aircraft model. Where the METS model generates equivalent gust inputs at the aircraft mixer, SORBET simulates turbulence by injecting gust velocity components to each of five blade element stations along each of the four main rotor blades, and the tail rotor of the aircraft math model (Fig. 1).

Precision hover tasks

The pilots were asked to perform a precision hover task in both on- and off-axis orientations. The visual scene was a reproduction of the visual scene at the United States Coast Guard Air Station at San Francisco International Airport where the flight tests in turbulence had been conducted. The scene was designed to give pilots enhanced position cueing in the on-axis orientation from objects located on the roof of the hangar (Fig. 2 top) and degraded cueing in the off-axis orientation by placing usable cues farther away in the visual scene (Fig. 2 bottom). The position tolerance for each of the tasks was desired (x - y position ± 10 ft, altitude ± 5 ft, heading ± 5 deg), and adequate (x - y position ± 20 ft, altitude ± 15 ft, heading ± 10 deg). The parameter settings for the turbulence models were the mean wind speeds (U_0 , ft/sec) and the turbulence intensities (σ , ft/sec) shown in Table 2, and for the METS model L , which was set to 53.7 ft. Four 2-minute records were recorded in each orientation for each configuration with each pilot.

The METS and SORBET turbulence models generate turbulent variations about a mean value. In the VMS, the

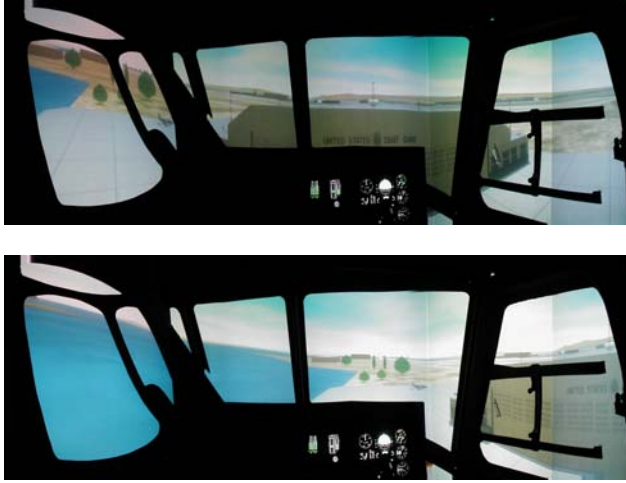


Fig. 2. Visual scene, on-axis (top), and off-axis (bottom)

aerodynamic effect or mean component of wind acting on the helicopter was generated by a separate subroutine. For all the tasks, the direction of the mean wind (V_o) was over the top of the hangar so that in the on-axis configuration, the aircraft had a head wind, and in the off-axis configuration, the wind was from the right of the aircraft. For all configurations except those denoted as uncorrelated, the magnitude of the mean wind speed (V_o) was correlated with the wind speed input to the turbulence model (U_o). The uncorrelated configurations used a fixed wind speed of 8-kts (13.5 ft/sec) as the mean wind (V_o). This configuration was selected to determine the impact of not replicating the mean wind component when

Table 2. Turbulence models/task settings

Configuration	Inputs to turbulence model			mean wind V_o (kts)	Aircraft orientation
	U_o (kts)	U_o (fps)	σ (fps)		
Calm	0	0	0	0	Off-axis
METS L1	12	20.3	2.5	12	On-axis Off-axis
METS L2	17	28.7	3.7	17	On-axis Off-axis
METS L2 uncorrelated	17	28.7	3.7	8	On-axis Off-axis
METS L2 varying*	17	28.7	3.7	17	On-axis Off-axis
SORBET L2	17	28.7	4.2	17	On-axis Off-axis
METS L3	22	37.2	5.4	22	On-axis Off-axis
METS L3 uncorrelated	22	37.2	5.4	8	On-axis Off-axis
METS L3 varying*	22	37.2	5.4	22	On-axis Off-axis
SORBET L3	22	37.2	5.5	22	On-axis Off-axis
METS L4	28	47.3	8.1	28	On-axis Off-axis
METS L4 uncorrelated	28	47.3	8.1	8	On-axis Off-axis

* U_o , σ and V_o are average values for record

implementing the METS model on in-flight simulators such as the Rotorcraft Aircrew Systems Concepts Airborne Laboratory (RASCAL) (Ref. 6). The varying configurations utilized time varying mean wind signals, the average values of which are listed in Table 2.

Vertical Motion Simulator

The NASA Ames Research Center Vertical Motion Simulator is a large amplitude, six-degree of freedom simulator (Fig. 3), which utilizes interchangeable cabs to simulate various aircraft (Ref. 7). Under normal operation, the simulator is kept within its operational limits via attenuation of high frequency accelerations by high frequency gains, and attenuation of low frequency accelerations by second-order high-pass "washout" filters. For the majority of the simulation, the cab was oriented perpendicular to the beam, so the simulated aircraft's longitudinal axis was aligned with the beam's short translational axis.

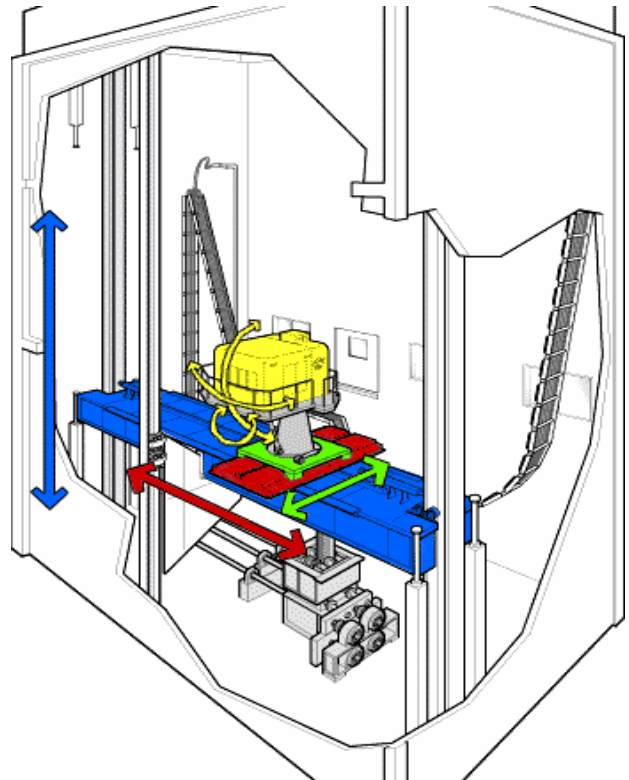


Fig. 3. NASA Ames Vertical Motion Simulator

The cab selected for this study was one of the five interchangeable cabs configured to replicate a UH-60 cockpit. The cab was developed for the Joint Shipboard Helicopter Integration Process (JSHIP) study (Ref. 8). The simulation utilized McFadden Systems loaders to produce realistic force-feel control cues and a seat shaker to replicate pilot seat vibrations. The JSHIP cab was selected for this simulation because of the expanded display (220-degree horizontal by 70-degree vertical) available to the

pilot (Fig. 2). The visual scene was produced by reflecting images off mirrors onto the rear of five adjoining flat panel screens, which resulted in a non-collimated image. A total visual time delay of approximately 70 msec was measured from the pilot control stick to the full screen image.

Aircraft math model fidelity

The UH-60 math model selected for this study was based on the modular programs that comprise the Sikorsky General Helicopter Flight Dynamics Simulation model which is commonly referred to as GenHel (Ref. 9). The non-linear, blade element model used in this simulation was an updated version, which incorporated modifications to the engine and drive train models (Ref. 10, 11). The model also included an aerodynamic phase lag correction implemented by NASA Ames to correct the low speed off-axis response (Ref. 12).

A check of the VMS GenHel model was done in the frequency domain by performing piloted lateral and longitudinal frequency sweeps in the VMS for comparison with frequency sweeps from flight. The sweeps were performed with the SAS on and with Flight-Path Stabilization (FPS) off. Frequency plots of pitch-rate-to-longitudinal-stick and roll-rate-to-lateral-stick from the VMS and flight tests were generated using CIFER® (Ref.

13) and are shown in Fig. 4. The frequency plots show good agreement between the VMS GenHel model and the test UH-60L¹ aircraft.

Checks of the model were also performed in the time domain. Pilot control input time histories from lateral, longitudinal, pedal and collective doublets conducted in a UH-60L were used as inputs to the VMS UH-60 GenHel model. An example of the simulation model and aircraft response to a lateral doublet is shown in Fig. 5. The agreement between the simulation model response and flight test data is representative of agreement of the short-term response to each of the doublet inputs.

The good agreement between the VMS GenHel UH-60 math model and the flight test UH-60L aircraft in both the frequency domain and time domain provided a high level of confidence that the simulation math model accurately represented the aircraft response in the frequency range of interest for piloted evaluations.

¹ The actual test aircraft was a prototype EH-60L Advance QuickFix aircraft that was modified for flight testing. All external antennas and aircraft survivability equipment were removed from the aircraft making the external airframe similar to a standard UH-60L. The test aircraft was operated with the directional and vertical gyros providing inputs to the flight control system to provide the same aircraft response as a standard UH-60L.

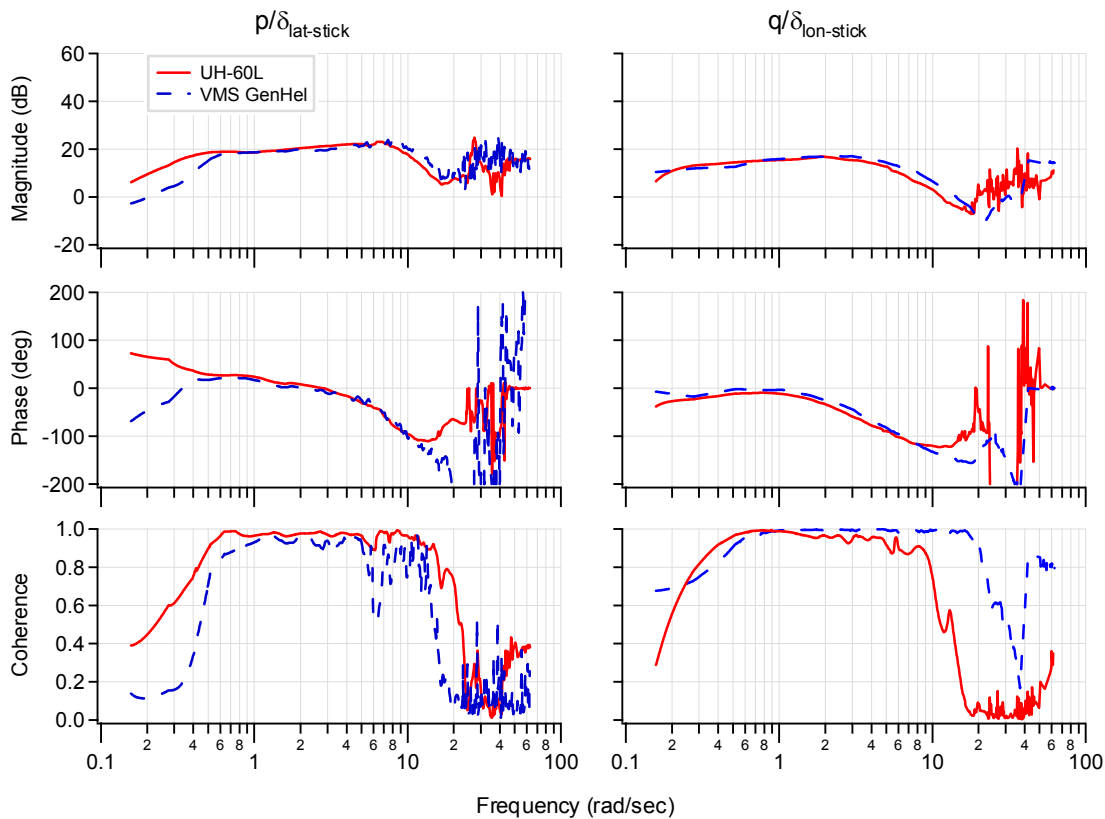


Fig. 4. Simulation and flight test lateral and longitudinal frequency sweeps

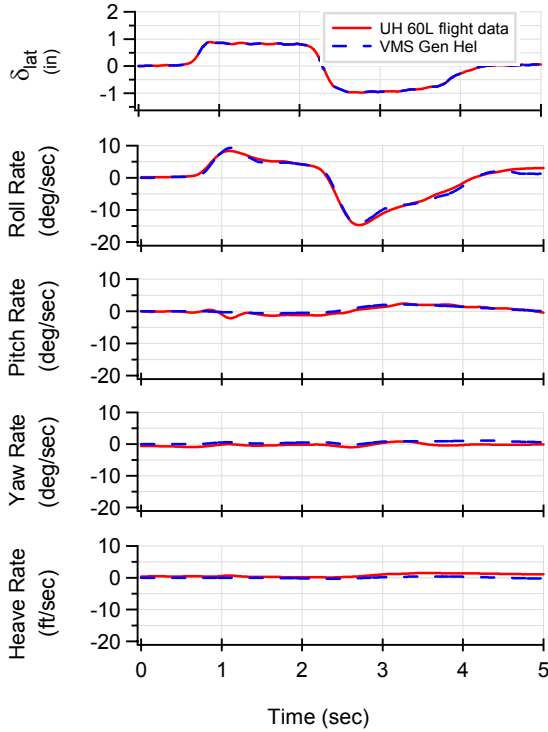


Fig. 5. Simulation and flight response to a lateral doublet

Results

Simulation fidelity

The frequency sweeps and doublets verified that the response of the simulation math model agreed well with the response of the aircraft. To measure the impact of the replication of the pilots' perceptual cues, a tight tolerance hover task was performed in the UH-60L test aircraft and the VMS without turbulence. In the VMS, the task was performed with motion and in a "fixed" configuration without motion. The Power Spectral Densities (PSDs) of the pilot inputs from the VMS and flight test obtained from CIPHER® are plotted in Fig. 6. The comparison shows that as the pilots' perceptual cueing is degraded, the magnitude of the PSD of the control inputs increases. There is also a corresponding degradation of the Handling Qualities Rating (HQR) from a HQR of 2 for flight to a HQR of 3 for simulation with motion, to a HQR 4.5 for simulation without motion. Table 3 shows a comparison of the pilot cutoff frequencies for the same three cases. The cutoff frequency is calculated from the autospectra of the pilot control time history as the frequency of the half power point bandwidth of the PSD function (Eq 1). The cutoff frequency is a good measure of pilot-in-the-loop crossover frequency and is correlated with pilot workload (Ref. 14).

Table 3. Relative pilot workload w/o turbulence

	ω_{co} (rad/sec)			
	lat	lon	dir	col
UH 60L	2.1	1.2	0.5	0.7
VMS w/motion	2.4	1.6	1.2	1.0
VMS fixed	2.8	2.3	1.4	1.3

$$\frac{\int_0^{\omega_{co}} G_{\delta\delta} d\omega}{\int_0^{\infty} G_{\delta\delta} d\omega} = 0.5 \quad (1)$$

These results show that in general, as the pilot's perceptual cueing degrades from flight to simulation with motion to simulation without motion, the power in the control inputs increases (increase in PSD magnitude), the pilot workload increases (higher cutoff frequency), and there is a corresponding degradation in handling qualities (increase in HQR). These results are consistent with previous studies where good agreement was found between the VMS GenHel math model and the flight-test aircraft, but simulation results showed an increase in pilot control and simulation rate PSDs, cutoff frequencies and

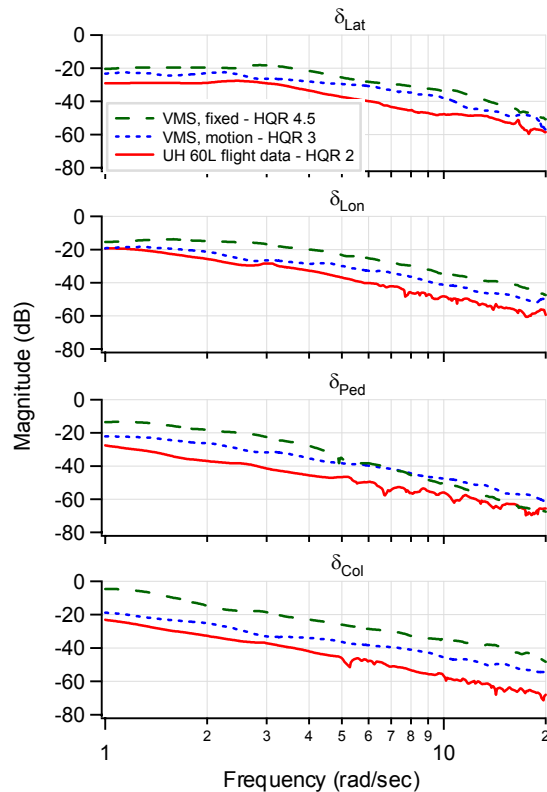


Fig. 6. Simulation and flight pilot control PSDs without turbulence

HQRs for equivalent tasks (Ref. 14). The differences are predominantly due to the reproduction of the pilots' perceptual cues in simulation. The differences in PSDs, cutoff frequencies and HQRs between simulation and flight are independent of the turbulence models and must be considered when comparing turbulence data from simulation with turbulence data from flight.

Comparison of METS with atmospheric turbulence

The data from the simulated tasks with increasing levels of turbulence were analyzed to determine the PSDs and cutoff frequencies of the control time histories. Fig. 7 shows plots of the pilot control PSDs for an on-axis hover task with 17-kt and 22-kt mean wind from flight and simulation. The increase in magnitude of the control PSD from simulation that was present without turbulence (Fig. 6) was also present with turbulence. The corrected curves in Fig. 7 have had an offset applied based on the differences between simulation and flight without turbulence (Fig. 6). With the offset due to simulation removed, the pilot control PSDs from simulation and flight agree relatively well. The pilots gave both simulation and flight a HQR of 3 for 17-kts mean wind. For the mean wind speed of 22-kts, pilots gave flight a HQR of 4 and

simulation a average HQR of 4.8. A comparison of the cutoff frequencies from simulation and flight for increasing turbulence in an off-axis orientation is shown in Fig. 8. The error bars indicate the 95 percent confidence interval when available, and the shaded regions on the figure denote the ADS-33E classification of winds (Ref. 15).

The general agreement between the pilot cutoff frequencies from simulation and flight in Fig. 8 and the adjusted pilot control and flight PSDs in Fig. 7, indicates that METS-generated turbulence produced a level of pilot workload in simulation comparable to the pilot workload from flight. Fig. 9 shows a comparison of simulation and flight average Root Mean Square (RMS) position error for increasing turbulence in an off-axis orientation. The figure shows that in general, the pilots were able to maintain approximately the same lateral, directional and vertical position error in simulation and flight. The longitudinal axis in simulation, however, shows somewhat larger position errors than the other axes. This is consistent with pilot comments that the visual scene appeared to be two dimensional, and lacking in depth and texture, which made it difficult for the pilots to regulate the longitudinal position.

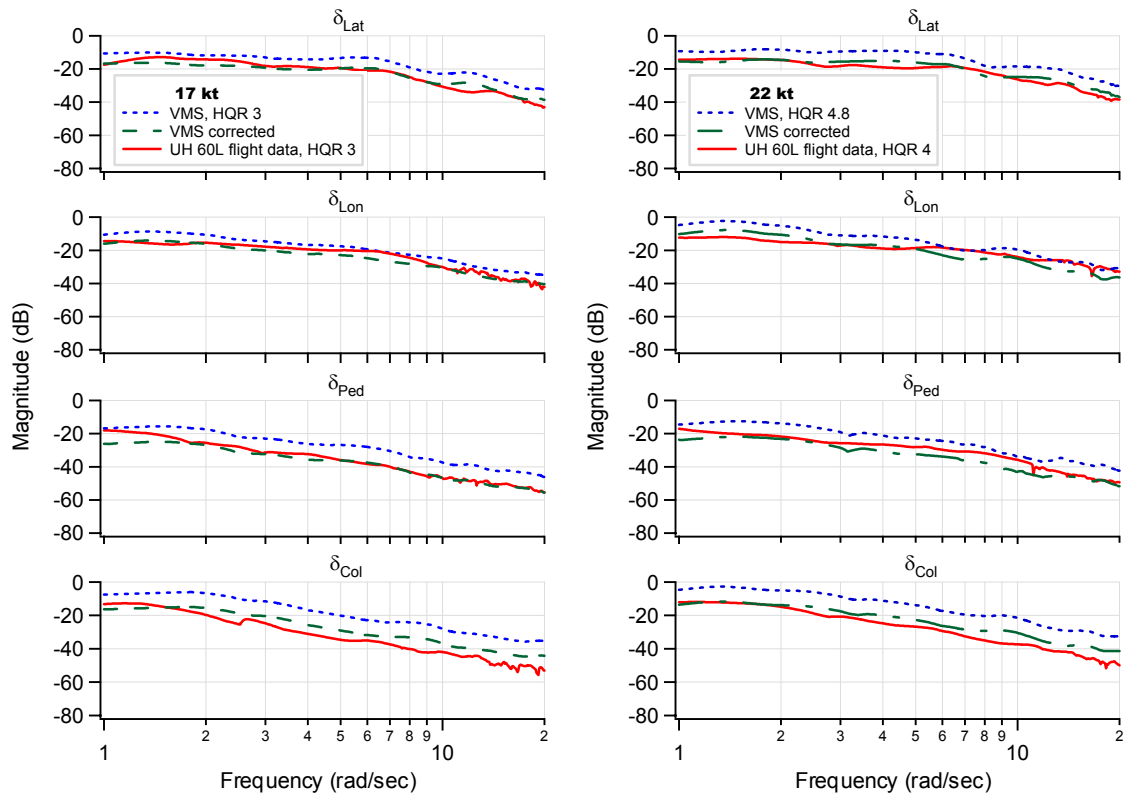


Fig. 7. Simulation and flight pilot control PSDs for 17-kts (left) and 22-kts (right) on-axis mean wind

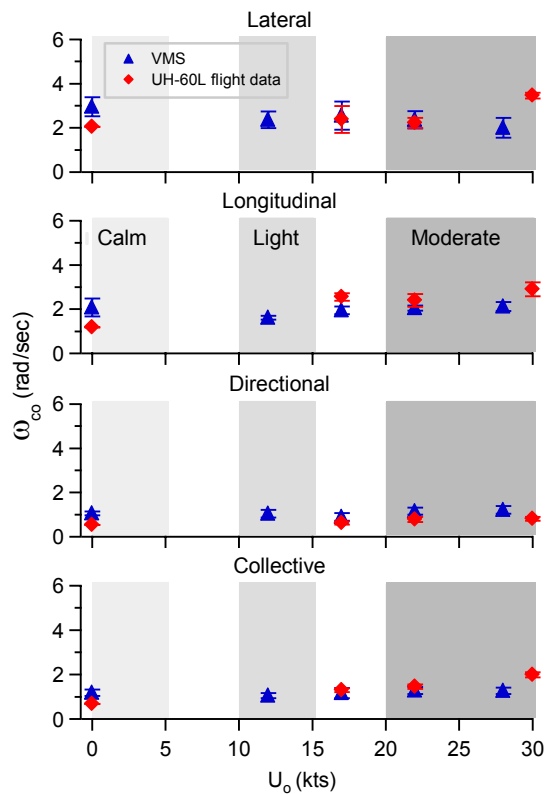


Fig. 8. Pilot cutoff frequencies from simulation and flight for off-axis orientation

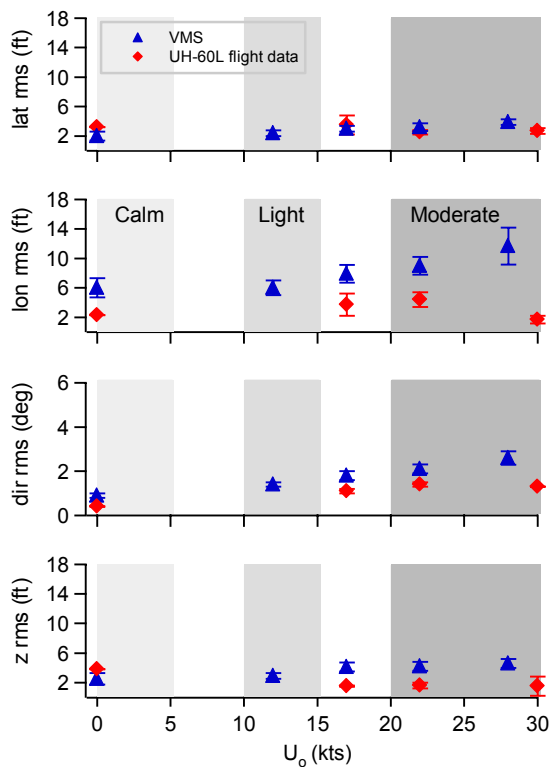


Fig. 9. RMS position error from simulation and flight for off-axis orientation

These results show that METS generated turbulence produced pilot and aircraft responses that were similar to the pilot and aircraft response of the UH-60L aircraft to atmospheric turbulence, and that the differences were mainly attributable to the inherent fidelity differences between simulation and flight.

Pilot cueing

In the off-axis orientation (Fig. 2, bottom), the visual position cueing was degraded from the on-axis orientation (Fig. 2, top). Fig. 10 shows a comparison of average RMS position errors for on- and off-axis orientations with increasing simulated turbulence. The lateral, directional and heave axes all show a slight increase in RMS position error in the off-axis orientation. The longitudinal axis, however, shows a significant increase in RMS position error in the off-axis orientation, which is predominantly due to the lack of cueing and depth in the visual scene. Fig. 11 shows that in general, the pilot cutoff frequencies for the same cases, remained about the same or slightly higher in the on-axis orientation. It is interesting to note that for the longitudinal axis, the pilot cutoff frequencies are similar for both orientations, while the RMS position errors increased notably in the off-axis orientation.

Fig. 12 shows the average simulation HQRs for on- and off-axis orientations. As the level of turbulence increased, the handling qualities degraded from Level 1 to

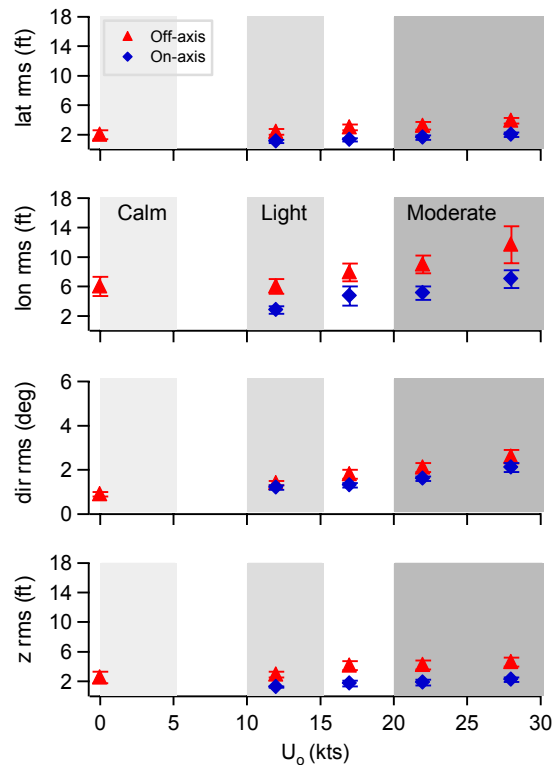


Fig. 10. RMS position errors from simulation for on- and off-axis orientations

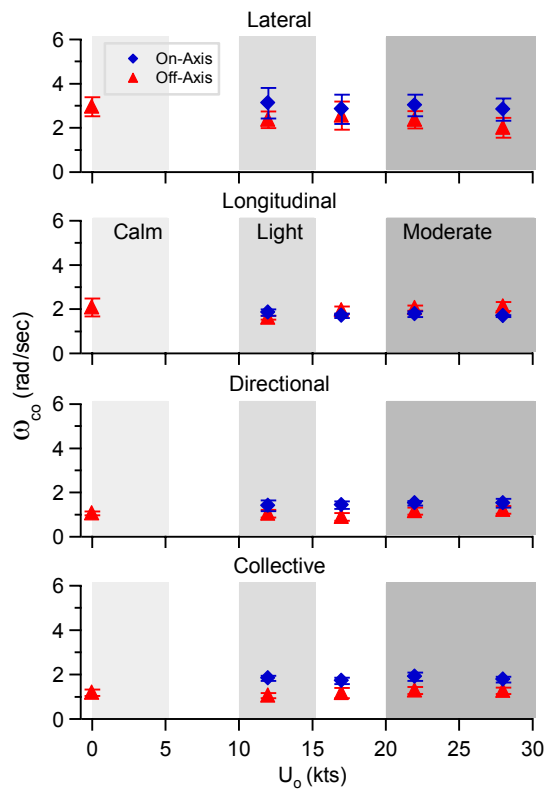


Fig. 11. Pilot cutoff frequencies from simulation for on- and off-axis orientations

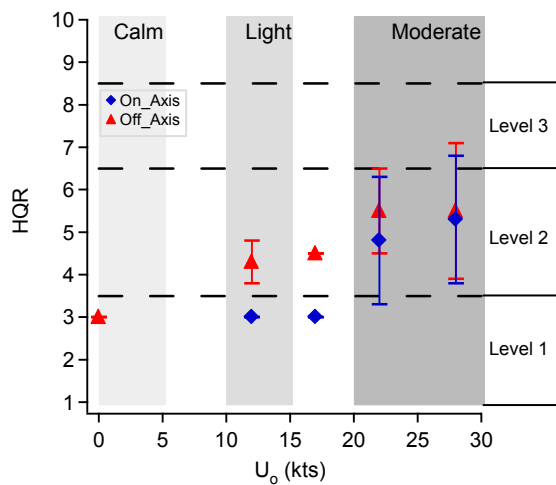


Fig. 12. HQRs from simulation for on- and off-axis orientations

Level 2. At light to light-moderate levels of turbulence (12-17 kts), the on-axis orientation produced Level 1 handling qualities, while the off-axis orientation produced Level 2 handling qualities. Once again, this was mainly

due to the lack of depth in the visuals and degraded cueing in the off-axis orientation. For these light to light-moderate levels of turbulence, visual cueing was an important factor in assessing the handling qualities in simulation. As the level of turbulence increased into the moderate level (greater than 20-kts), the differences in cueing did not have as significant an affect on the HQR.

Pilot control strategy

Fig. 13 shows a comparison of pilot cutoff frequencies from simulation for increasing levels of turbulence in the off-axis configuration. In general, the cutoff frequencies for pilot B were higher than pilot A, most notably in the lateral axis where the cutoff frequencies for pilot B were about 1 rad/sec higher than pilot A for every turbulence level. This is consistent with comments from pilot B indicating that an aggressive control strategy was used at all levels of turbulence. Pilot A, however, commented that an aggressive control strategy was not used, especially at low levels of turbulence for fear of exciting other axes. Even though the cutoff frequencies for pilot B at all levels of turbulence were consistently higher in the lateral axis, the lateral RMS position errors for both pilots in Fig. 14 are approximately the same.

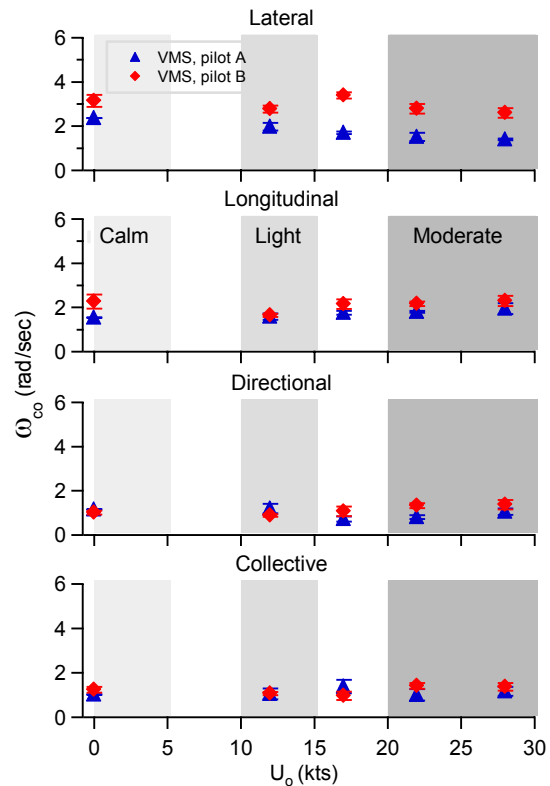


Fig. 13. Cutoff frequencies for pilot A and pilot B from simulation for an off-axis orientation

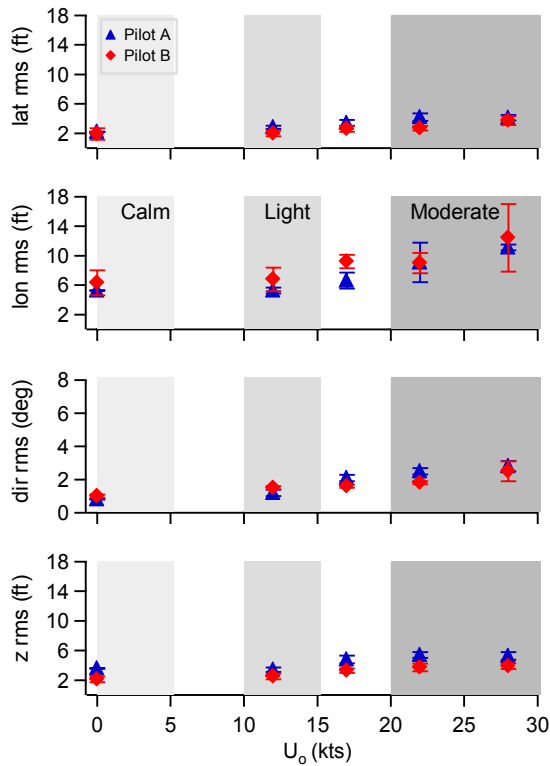


Fig. 14. RMS position errors from simulation for an off-axis orientation

Impact of mean wind

As stated earlier, the METS model generates the turbulent component of atmospheric disturbances, but not the steady or mean wind component. In the VMS, the effects of winds are simulated by a subroutine which includes mean winds from a predetermined earth-fixed direction into the aircraft body-fixed velocities. Fig. 15 shows a comparison of the pilot cutoff frequencies from METS generated turbulence for cases where the mean wind V_o was correlated with U_o , set at a constant 8-kts and varying with time about an average value of U_o . Fig. 16 is a comparison of the HQRs for the corresponding cases. The general agreement between pilot cutoff frequencies for all three mean wind inputs shows that the pilots were not able to differentiate between the various mean wind settings. This indicates that when implementing the METS model in in-flight simulators, the inability to replicate the mean wind should not have a significant impact on the results.

Comparison of METS and SORBET turbulence

Turbulence was also simulated using the SORBET model at the two levels listed in Table 2. The pilots were asked to perform the same tight tolerance hover tasks with SORBET generated turbulence that had been performed with METS generated turbulence. Fig. 17 shows a

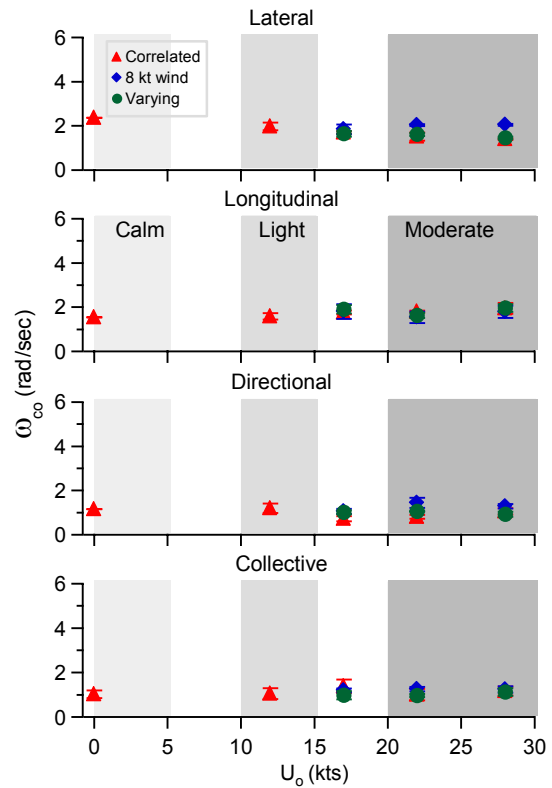


Fig. 15. Pilot cutoff frequencies for correlated, varying and 8-kts mean wind (V_o) from simulation for an off-axis orientation

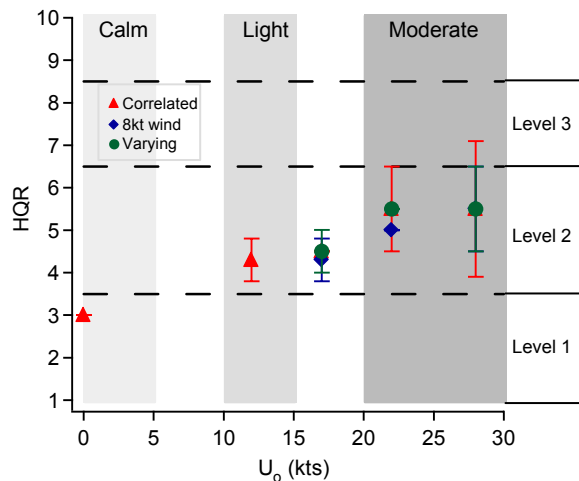


Fig. 16. HQR for correlated, varying and 8-kts mean wind from simulation for an off-axis orientation

comparison of the PSDs of the pilot control inputs from METS and SORBET simulated turbulence for pilot B, and from flight test data. The figure on the left is for a mean wind speed of 17-kts in an off-axis orientation, and the figure on the right is for a mean wind speed of 22-kts in an on-axis orientation. Fig. 18 is a comparison of the PSDs of the flight test and simulated aircraft rates for the same records.

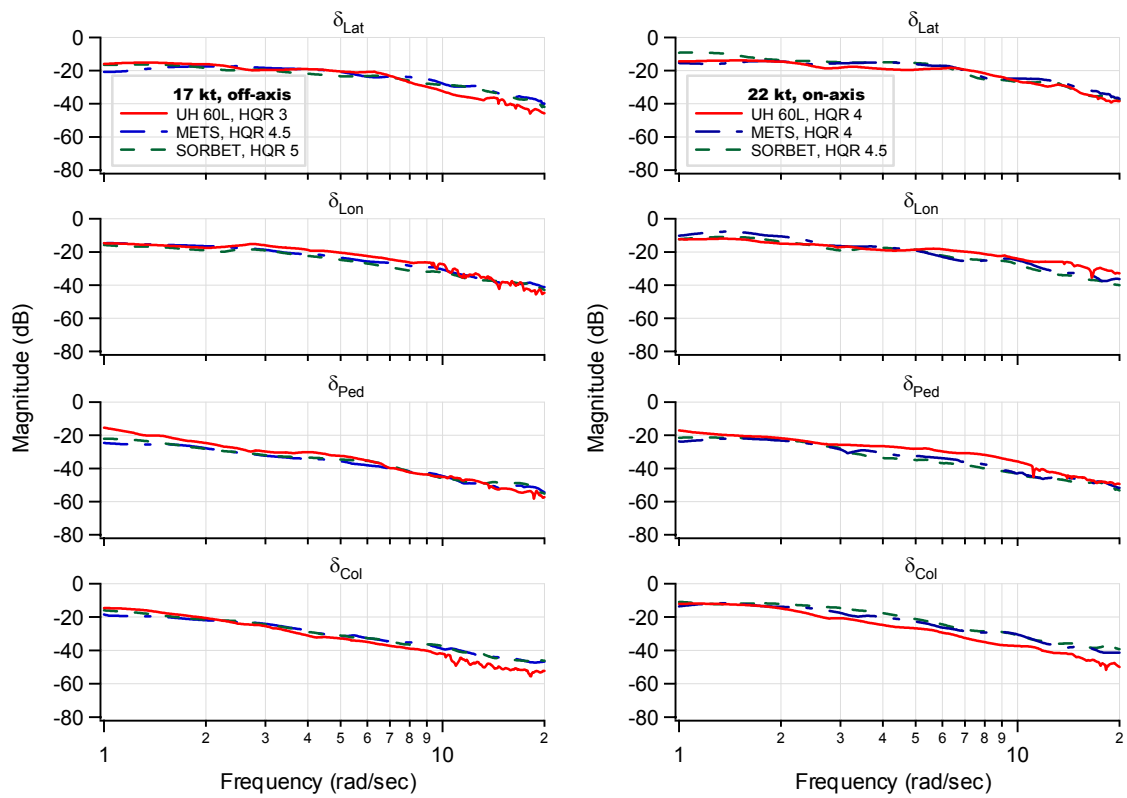


Fig. 17. PSDs of pilot inputs from flight test, corrected METS and corrected SORBET generated turbulence

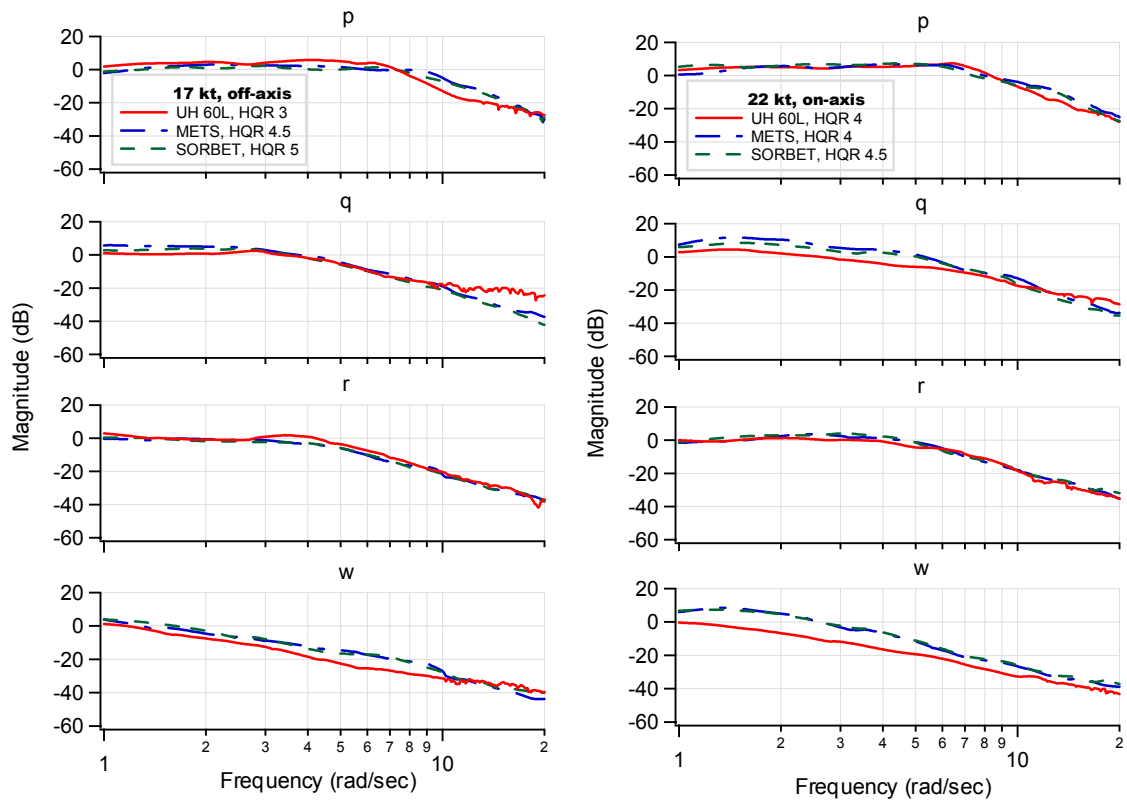


Fig. 18. PSDs of rates from flight test, corrected METS and corrected SORBET generated turbulence

The PSDs of the pilot control inputs and the corresponding aircraft rates from METS and SORBET generated turbulence agree quite well and, with the offset for simulation applied (Fig. 7), both agree relatively well with the PSDs from flight data. At the 22-kt level in the on-axis orientation, the magnitude of the PSDs of the pilot collective and corresponding aircraft heave rate from simulation show an increase in magnitude when compared to flight test data. The pilot comments from flight indicated that the control that required the highest workload was the longitudinal cyclic followed by the collective. In simulation, the pilot commented that the control that required the highest workload for the 17-kt case was the collective followed very closely by the longitudinal cyclic. At the simulated 22-kt level, the pilot commented that the collective control required a higher workload than any of the other controls. The increase in collective activity is evident from the increase in the magnitude of the collective and heave rate PSDs from simulation when compared to flight. Pilots in both simulation and flight indicated that the directional control required the least effort. The pilot also noted that SORBET generated turbulence at the 22-kt level required large amplitude, low frequency control inputs to maintain position, particularly in the heave axis, which was the main factor contributing to the slightly degraded handling qualities ratings of SORBET compared to METS (Fig. 17, 18).

Fig. 19 shows a comparison of pilot control cutoff frequencies from flight test data and simulated turbulence generated by SORBET and METS. It should be noted that the simulation data are from one pilot (pilot B) while the flight test data are from two different test pilots, and as Fig. 13 shows, the control strategy of different pilots can have a significant impact on cutoff frequencies for identical tasks. At the 17-kt level in an on-axis orientation, the cutoff frequencies from simulation and flight agree relatively well (Fig. 19). At the 22-kt level in an off-axis orientation, the cutoff frequencies for METS and SORBET are in agreement for all controls except the lateral cyclic, where the cutoff frequency for SORBET turbulence is 1.3 rad/sec lower than for METS turbulence. The difference indicates that at the higher level of turbulence, the pilot workload in the lateral axes was concentrated at lower frequencies with SORBET than with METS. This is consistent with pilot comments that in general, SORBET generated somewhat larger amplitude, low frequency turbulence inputs to the aircraft than METS.

The general agreement between the pilot control and aircraft response metrics from turbulence generated with both simulation models and flight test data provides a good level of validation of the theoretical blade element turbulence modeling methodology. The most notable difference between turbulence generated by the two models is the tendency for SORBET to produce large amplitude, low frequency gusts, which the pilots found objectionable and inconsistent with the actual aircraft's response to atmospheric disturbances.

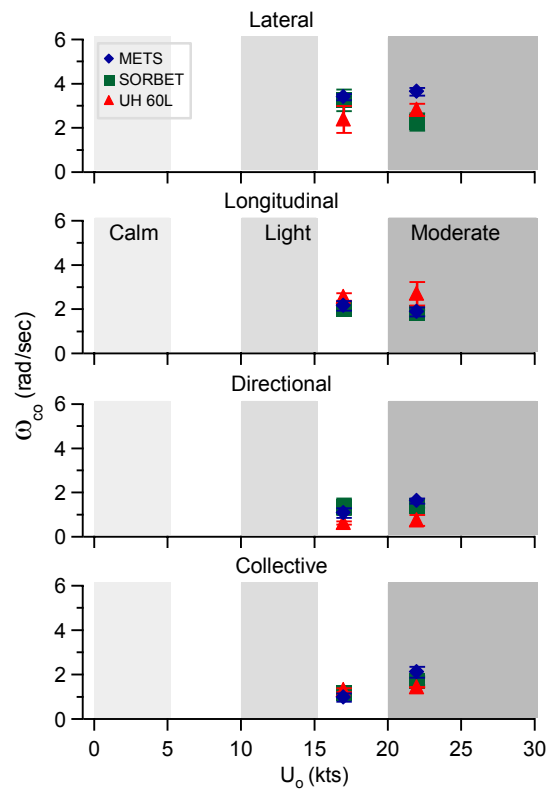


Fig. 19. Pilot cutoff frequencies from flight and simulated turbulence (pilot B) for 17-kt, on-axis and 22-kt, off-axis cases

Future work

One of the parameters in the METS model, the turbulence integral scale length L , is by definition a parameter of the atmospheric turbulent flow field and is strongly related to the altitude above the ground. For rotorcraft such as the Black Hawk operating in near Earth turbulence, it is common to have turbulence scale lengths on the same order of magnitude as the rotor radius of the helicopter (Ref. 16). During the initial development of the METS model, L was set to the rotor diameter of the UH-60L helicopter. Future research will investigate the scaling of the METS model with rotor diameter. Later, flight tests will be conducted with the RASCAL in-flight simulator utilizing the METS model to evaluate control law disturbance rejection characteristics and the impact of turbulence on handling qualities for selected ADS-33E maneuvers.

Conclusions

A complete hover/low-speed Mixer Equivalent Turbulence Simulation (METS) model for the UH-60 helicopter has been developed. The model is scalable for varying levels of turbulence, and is suitable for flight simulation and control system design. A piloted simulation was conducted in the NASA Ames Research

Center Vertical Motion Simulator to evaluate the METS model against flight test data and a rotating frame turbulence model, Simulation Of Rotor Blade Element Turbulence (SORBET). The simulation reproduced the visual scene and tasks from flight tests conducted with an instrumented UH-60L hovering in turbulence. With adjustments made for the inherent differences between simulation and flight, a direct comparison of simulation and flight data metrics for equivalent tasks was presented. Some specific conclusions are:

- 1) Satisfactory quantitative validation of the METS model was accomplished using aircraft response and pilot control metrics.
- 2) Satisfactory qualitative validation of the METS model was accomplished using handling qualities ratings and pilot comments.
- 3) Validation of a more complex rotating frame blade element turbulence model (SORBET) was accomplished through comparison with the empirically derived METS turbulence model and flight test data.

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