**Pilot Workload Investigation for Rotorcraft Operation in Low-Altitude Atmospheric Turbulence**

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**Abstract**

This paper aims to investigate pilot workload for rotorcraft operations in low-altitude atmospheric turbulence. A novel low-altitude turbulence model derived through the pre-warped Tustin transformation is used to modify the classic distributed turbulence model. The distributed model is then validated against the von Kármán spectra and is integrated into a flight simulation environment that consists of a high-fidelity nonlinear flight dynamics model and a multi-loop compensatory pilot model. The simulation responses and pilot controls in turbulence have been compared against flight test data for operations in bluff-body and freestream turbulence conditions. The effect of terrain roughness on pilot workload is analyzed. The results show that low-altitude turbulence becomes more intense and has smaller length scales over rougher terrain for the same conditions of the reference wind speed and altitude. Moreover, the effect of terrain roughness can increase pilot workload with increasing airspeed and decreasing flight altitude.

***Keywords*:** Rotorcraft; Pilot workload**;** low-altitude turbulence; terrain roughness; pilot model; simulation

# Introduction

Rotorcraft often perform nap-of-the-Earth flight tasks above mountains, hills, farms, and cities. The low-altitude atmospheric turbulence induced by rough terrain can result in extra pilot workload [1-3]. Pilots are required to divert more attention to aircraft handing such that other mission performances can be degraded. Moreover, severe turbulence leads to a more dangerous flight condition or even worse, loss of the aircraft. Therefore, it is critical to investigate pilot workload to improve flight safety and mission performance when performing operations in low-altitude atmospheric turbulence.

The modeling of atmospheric turbulence for rotorcraft flight simulations has attracted much attention since the 1980s. The body-fixed turbulence modeling approach used for fixed-wing aircraft [1-4] was demonstrated as unsuitable for rotorcraft due to the main rotor rotational motion. Later, a high-fidelity blade-centered method [5, 6] was proposed by modeling turbulence components at blade segments with their cross-correlation relationships. However, its computational efficiency was not suitable for real-time simulation applications [7]. McFarland and Duisenberg [8] proposed an improved structure for the turbulence modeling of rotorcraft. Two turbulence filters were fixed in front of the rotorcraft with the “frozen field” hypothesis and the turbulence components were transported backward to cover all of the aerodynamic elements for the forward flight of the aircraft. Ji et al. [9] extended this work and developed a distributed model by arranging cross-correlated filters on the front surface of the aircraft with the “frozen field” hypothesis. The turbulence components were convected backwards to form a three-dimensional turbulence field with the forward flight of the aircraft. They were produced by high-order filters with the approximate von Kármán spectra [10] and correlated by a linear transformation with the Cholesky factor. Anderson [11] simulated the highly structured turbulence over a clifftop using a Computational Fluid Dynamics (CFD) method. The CFD data were integrated into a rotorcraft model via lookup-tables of the flow field for the analysis of rotorcraft vibrations [11] and the trajectory planning of unmanned aircraft [12]. Although CFD methods have been widely used for time-varying flow fields around man-made structures such as ships [13-15], vehicles, and buildings etc., the extensive computations required to generate the flow fields have limited their application in natural turbulence modeling for aircraft flight analysis. Compared to the physics-based turbulence models, the Control Equivalent Turbulence Input (CETI) models [16, 17] provide a data-driven turbulence modeling approach for rotorcraft. It produces extra control inputs to rotorcraft with specific power spectral densities to represent the same effect of turbulence. The model parameters were identified from flight test data. The CETI models were widely used for rotorcraft simulations at low speeds [18, 19] due to its high applicability in this range.

Despite the wide validation and applications of the preceding turbulence models, both physics-based and data-driven models cannot capture the effect of the roughness characteristics of underlying terrains present in low-altitude turbulence regimes. MIL-F-8785C [20] is widely used to determine turbulent length scales and intensities, but they have only functions of altitude with a reference wind speed to quantify the vertical turbulence intensity. They may be sufficient for the simulation of airplanes take-off and landing on a specific terrain type of airport, however, rotorcraft often fly above terrains with completely different features. Recent research [21] showed that the measured length scales and intensities of the marine turbulence were different from those defined in the MIL-F-8785C. References [22-25] have demonstrated that both turbulence intensities and length scales were related to the roughness characteristics of the underlying terrains. Therefore, the current physics-based turbulence models should be updated both in terms of the turbulence intensities and length scales related to terrain roughness if they are to be used for examining rotorcraft operations in the presence of low-altitude atmospheric turbulence. The aforementioned CETI models are also not valid when the terrain features change since they were derived from the flight tests over terrain with a specific roughness characteristic.

The properties of low-altitude atmospheric turbulence have been widely investigated by the meteorology community [24-28], which provides an opportunity to explore the effect of terrain roughness on pilot workload for rotorcraft operations in turbulence. In the following section, a low-altitude atmospheric turbulence model is proposed with the algorithms derived from the pre-warped Tustin transformation to update the classic distributed model. The pilot-model-in-the-loop simulation section describes the flight dynamics model and multi-loop compensatory pilot model for the simulation of rotorcraft operations in turbulence, which is validated against flight test data. The effect of terrain roughness on pilot workload section discusses the effect of terrain roughness on pilot workload in turbulence. Finally, conclusions will be drawn.

# Low-Altitude Turbulence Model for Rotorcraft Flight Simulation

* 1. *Development of Low-Altitude Atmospheric Turbulence Model*

Low-altitude atmospheric turbulence is usually stronger and more susceptible to weather conditions than high-altitude turbulence, such as flow above rough terrain, cold or warm weather fronts, thunderstorms, or aircraft wakes, etc. This paper focuses on the mechanical turbulence below 300 m mainly caused by airflow around solid objects, such as hills, mountains or man-made structures. Many studies [26-28] have demonstrated that low-altitude turbulence in the atmospheric boundary layer above different terrains satisfies the Kolmogorov -5/3 decay law and that the von Kármán spectra were still suitable for engineering applications. When the one-dimensional von Kármán spectra [29] are transformed into the spatial frequency form, the results are,

where , , and are the power spectral densities for the longitudinal, lateral, and vertical turbulence components, respectively. represents the spatial frequency. , , and , , are the turbulence intensities and length scales, respectively. is Archimede's constant.

Equation (1) shows that turbulence magnitudes and power distributions are determined by two parameters: the intensities and length scales. This paper employs the results from the meteorology community [30] with consideration of the roughness characteristics of the local terrain to calculate the intensities and length scales for low-altitude turbulence modeling. The laws are expressed as functions of the local terrain roughness, mean wind speed, and altitude above ground. The variation of the mean wind speed at altitudes below 300 m is generally considered by the power law,

where is the mean wind speed at the altitude of m above ground, is the mean wind speed at the reference altitude which usually takes a value of 10 m. The power index, , is related to terrain roughness. The power index law proposed by Counihan [23] based on the data of four distinct terrain types and further validated by Gualtieri [25] is employed here for the neutral atmosphere conditions,

where represents terrain roughness.

Based on the wind speed variation, turbulence intensities up to 300 m are determined with,

and turbulent length scales are determined by the following laws,

Combination of Eqs. (1)-(5) gives a complete description of the low-altitude atmospheric turbulence model.

* 1. *Turbulence Modelling with Pre-warped Tustin Transformation*

Turbulence components were generally produced by passing the samples of band-limited white noise through shaping filters with prescribed spectra [31]. The Dryden turbulence model has been widely used due to its simple form and ease of implementation. However, the von Kármán spectra were more recommended for rotorcraft applications to improve simulation fidelities in low-speed flight conditions [10]. The most challenging problem for the application of the von Kármán spectra in this method arises from their irrational forms. The third- and fourth-order shaping filters proposed by Ji et al. [10] for turbulence modeling have been demonstrated to have validity for a large frequency range and are suitable for rotorcraft simulations even in low-speed and low-altitude flight conditions. Based on the “frozen field” hypothesis and transformed from the spatial frequency to the temporal frequency [31], the high-order shaping filters are expressed with the following form,

where , , and are the shaping filters for the longitudinal, lateral, and vertical turbulence components, respectively. are the dimensionless frequencies and represents the airspeed. The coefficients are presented as follows,

=0.25, =0.0244, =1.19, =0.167, =0.0170;

=2.618, =0.12981, =0.0178, =2.083, =0.823, =0.08977, =0.0129.

The pre-warped Tustin transformation [32] is used to discretize the shaping filters for highly accurate turbulence modeling in the frequency range of interest,

where is the pre-warped frequency, is the simulation step, and is expressed as follows,

Compared to the case without pre-warping, the pre-warped Tustin transformation could improve the accuracy of discretization in the frequency range around the pre-warped frequency [32]. This is very important for rotorcraft simulation in atmospheric turbulence in that if specifying rad/s, it achieves a high-precision turbulence modeling in the frequency range (1-10 rad/s) of interest for pilot workload [33]. The longitudinal shaping filter is taken as an example to show the discretizing procedure. Substituting Eq. (7) into the longitudinal shaping filter of Eq. (6), we obtain

where is,

and the coefficients and are presented in Table 1.

Considering that,

where represents the longitudinal turbulence component, and is the ideal white noise with a unit spectrum, that is,

However, the band-limited white noise with a unit variance is more widely used in practice, that is

where represent the variance of the white noise , represents the power spectral density, and is the Nyquist frequency.

Table 1 Coefficients of difference equations for turbulence modeling

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| Longitudinal | Lateral |
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Combining Eqs. (12) and (13), we obtain,

As a consequence, there exists a proportional relationship between and ,

Then, we arrive at

Finally, substituting Eq. (9) into Eq. (16), after cross multiplying and simplifying, the difference equation for the longitudinal turbulence components is obtained as,

where and are the longitudinal turbulence component and band-limited white noise at the time , and

By conducting the same procedure to the lateral shaping filter of Eq. (6), the difference equation for the lateral turbulence components is expressed as,

where is the lateral turbulence component at the time ,the coefficients and are presented in Table 1, as well as is,

The difference equation for the vertical turbulence components is similar to that for the lateral case in Eq. (19). Thus, low-altitude atmospheric turbulence can be simulated by Eqs. (17) and (19). Furthermore, the proposed turbulence modelling approach is easily implemented into rotorcraft flight simulations due to the computational simplicity and efficiency of the differential equations as well as the high accuracy of the von Kármán spectra.

* 1. *Distributed Model for Rotorcraft Flight Simulation*

The preceding turbulence modelling approach will be incorporated into the classic distributed model [9] to form a low-altitude atmospheric turbulence field for rotorcraft flight simulation. It has a three-dimensional turbulence field covering every aerodynamic surface of the object rotorcraft, as shown in Fig. 1. The turbulence field overlaps with a cuboid *ABCDEFGH* that is fixed with the rotorcraft center of gravity (CG) and rotates along the lateral and vertical axes to keep the front surface *ABCD* perpendicular to the airspeed . The width of the turbulence field is , the length is , and the height is , where is the main rotor radius, and are determined by the rotorcraft geometry.



Fig. 1. Distributed turbulence model and axis definitions [9].

To create the turbulence field, a total of cross-correlated filters are arranged evenly on the surface *ABCD* inrows withfilters in each row. The longitudinal turbulence components are taken for example to show how to form the cross-correlated filters. First, a total of longitudinal turbulence components are produced independently at the simulation time , and denoted as , where represents the sequence of the simulation steps, , and . Then, the covariance matrix between the dependent turbulence components can be calculated by the von Kármán theory. More specifically, the element in the row and th column is,

where , , , , , and 1.339. and are the coordinates of the th and th filters respectively, is the gamma function, and is the modified Bessel function of second kind.

Finally, considering the normal distribution properties of the independent turbulence components, the linear transformation method with the Cholesky factor has been theoretically demonstrated as optimal for the production of dependent components [34]. The desired lower triangular factor is solved with the Cholesky factorization [35] to the covariance matrix ,

The turbulence components of the cross-correlated filters arrive from the following transformation,

where and are the vectors of the dependent and independent turbulence components,

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where and are the dependent and independent turbulence components of the th turbulence filter in the lateral direction and the th in the vertical direction at the time .

The dependent lateral and vertical turbulence components are produced by repeating the preceding procedure. Hence, the cross-correlated turbulence filters are formed.

Taylor’s “frozen field” hypothesis [29] is also employed to form the turbulence field. From this hypothesis, the discrete turbulence components produced by the filters at the surface *ABCD* are fixed at the inertial positions where they are generated. On this basis, the discrete turbulence components produced on the surface *ABCD* are distributed backward to fill up the turbulence field when the rotorcraft and the cuboid *ABCDEFGH* are flying forward with the airspeed . Thus, the low-altitude atmospheric turbulence field is formed.

To integrate the distributed turbulence model into a rotorcraft flight dynamics model, two coordinate systems are defined. One is the North-East-Down (NED) system, where the -axis points north and the -axis points east with both parallel to the geoid surface, as well as the -axis points downward, toward the Earth surface, as shown in Fig. 1. The other is a turbulence system, where the -axis points toward the opposite direction of the airspeed , the -axis points toward the left direction of the object rotorcraft, perpendicular to the -axis, and the -axis points perpendicular to the plane and satisfies the left-hand rule. Considering that the turbulence system points opposite to the wind system, the transformation matrix from the NED system to the turbulence system is,

where and are the climb and heading angles of airspeed, defined as,

where , , and are the longitudinal, lateral, and vertical components of airspeed in the NED system, respectively.

Considering that the turbulence field is fixed to the CG of the object aircraft, the coordinates of a rotorcraft aerodynamic element, taking the fuselage for example, in the turbulence system are calculated by,

where is the transformation matrix from the body system to the NED system, and are the coordinates of the fuselage and CG in the body system, as well as  and are the coordinates of the fuselage and CG in the turbulence system.

With the coordinates , the turbulence components of the fuselage are obtained by the nearest interpolation to the turbulence field and denoted as . After transforming into the NED system, the turbulence components of the fuselage for the flight dynamics model are,

where is the transformation matrix from the turbulence system to the NED system, are the turbulence components of the fuselage in the NED system.

With coordinates offered from the flight dynamics model and by repeating the above procedure, turbulence components of each aerodynamic element of the object rotorcraft can be calculated and then transferred back to the flight dynamics model for simulation.

* 1. *Initial Validation of the Turbulence Model*

The statistical property and accuracy of the low-altitude turbulence model are discussed before further insight into its effect on rotorcraft operations. The distributed model is simulated for a UH-60 rotorcraft [36] facing into freestream turbulence. The main rotor has four blades and the radius and rotational speed are 8.17 m and 27 rad/s, respectively. The wind speed is set as =8 m/s referring to light turbulence of the MIL-F-8785C [20]. Four terrain types of short grass, farmland, city center, and rugged hills are discussed with =0.01, 0.1, 1 and 3 m, respectively [30]. Forty turbulence filters are arranged in front of the rotorcraft with two rows and 20 filters in each row. The simulations are conducted at an altitude of 10 m.

Figure 2 shows the variation of wind speed with altitude and terrain roughness. Terrain roughness has an important impact on the variation of wind profiles with altitude. Although the wind speeds are the same at the reference altitude of 10 m, the wind profile over a rougher terrain grows much more rapidly. Since rotorcraft often perform flight tasks with low ground speed, terrain roughness has a significant impact on rotorcraft operations near the ground by affecting the wind speed.

Figure 3 shows the variation of turbulence intensities with altitude and terrain roughness. The MIL-F-8785C values with the reference wind speed of 8 m/s are calculated with Eq. (A1) in the Appendix for comparison. As can be seen, turbulence intensities increase rapidly with increased terrain roughness. This is due to two reasons: the increasing wind speed and turbulence kinetic energy with terrain roughness. Compared to the proposed low-altitude turbulence model, the MIL-F-8785C predicts results similar to the cases with the terrain roughness of 0.01-0.1 m. This is reasonable in that the MIL-F-8785C is oriented to fixed-wing aircraft which only take off and land on runways which are typically surrounded by a patchwork of grass and bushes. Furthermore, both models indicate that the most severe turbulence occurs at low-altitude flight conditions.



Fig. 2. Variation of wind speed with altitude and terrain roughness.

Figure 4 shows the variation of turbulent length scales with altitude and terrain roughness. The MIL-F-8785C results are included for comparison. As shown there, the longitudinal and lateral length scales increase with altitude and terrain roughness, while the vertical length scales are only affected by altitude. In contrast, the MIL-F-8785C predicts much larger values of the length scales than all of the results by the proposed low-altitude turbulence model. The length scales have a direct effect on turbulence spectra by changing the zeros and poles of the shaping filters in Eq. (6), and therefore, the proposed formulas in consideration of terrain roughness are more suitable for rotorcraft simulations near the ground.

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| Fig. 3. Variation of turbulence intensities with altitude and terrain roughness. | Fig. 4. Variation of turbulent length scales with altitude and terrain roughness. |

Figures 5 and 6 show the results of the simulated turbulence components in the time and frequency domains, respectively. The theoretical von Kármán spectra are included in Fig. 6 for validation. As observed in Fig. 5, the turbulence components over rougher terrain with =1 m shows higher magnitude and more high-frequency contents than the case with = 0.1 m. The same conclusion is also obtained from Fig. 6. Furthermore, the simulated turbulence spectra agree well with the theoretical von Kármán spectra in the frequency range (1-10 rad/s) for both cases. The pre-warped Tustin transformation approach of turbulence modeling captures the effect of terrain roughness on turbulence velocities in frequencies from 1-10 rad/s, which are the most important frequencies from a pilot workload perspective.

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| Fig. 5. Comparison of turbulence components between different terrain roughnesses. | Fig. 6. Comparison of turbulence spectra between different terrain roughnesses. |

Figures 7 and 8 show the simulated turbulence spectra for the root and tip segments of a rotational blade, which were calculated from the simulated turbulence velocities in the time domain. The theoretical von Kármán spectra are included for validation. The terrain roughness is 0.1 m. As shown in Fig. 7, the simulated turbulence spectra at the blade root reach a good agreement with the theoretical spectra at the low frequencies, and high-frequency peaks appear at 27 rad/s, 54 rad/s, and 81 rad/s etc., which are integer multiples of the rotor speed. The reason is that the periodically rotational motion of the blade segment in the random turbulence field transfers turbulence energy from low frequencies to the high-frequency peaks [8]. Figure 8 shows that there is a relatively larger difference between the simulated and theoretical vertical spectra than the comparison results of the longitudinal and lateral spectra. This is because the vertical turbulence length scale, which is 7 m at this case, is much less than the longitudinal and lateral length scales of 64.7 m. As a result, the vertical turbulence components are much more random than the longitudinal and lateral components along the blade tip route, and therefore more vertical turbulence energy is transferred away from the low-frequency range.

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| Fig. 7. Turbulence spectra at blade root. | Fig. 8. Turbulence spectra at blade tip. |

Overall, the low-altitude atmospheric turbulence simulation model shows a good match with the theoretical von Karman spectra over different terrain types and the updated distributed model captures the effect of rotational velocities on the turbulence components experienced by main rotor blades.

# Pilot-Model-in-the-Loop Simulation

* 1. *Flight Dynamics Model*

The mathematical model from Chen’s research [37] is employed to simulate a UH-60A helicopter. It is a high-order nonlinear flight dynamics model and was widely validated and used in flight control design and simulation [38], as well as trajectory optimization for rotorcraft autorotations [39]. The effect of the main rotor induced velocity on turbulence should be considered when integrating the distributed model into the rotorcraft model for a straight and level flight at a constant airspeed. The induced velocity would speed up the aft convection of the turbulence components in that at low speed, the induced velocity rather than the actual airspeed of the aircraft can dominate the movement of the turbulence field. This speedup effect becomes negligible as the induced velocity is much smaller than the rotorcraft airspeed when , where represents the rotorcraft airspeed and is the main rotor induced velocity in hover state. Therefore, the speedup effect of the main rotor induced velocity for low-speed flight is considered by correcting the transfer speed of the turbulence field, that is

where represents the airspeed input for the turbulence model.

Then, the effect of atmospheric turbulence on aircraft aerodynamics is considered by superimposing the turbulence disturbances directly to the local inflow velocities of the main rotor blade segments, fuselage, horizontal stabilator, vertical fin, and tail rotor. The integrated distributed turbulence model and rotorcraft flight dynamics model can be expressed as follows,

where is the state vector of the aircraft states,

and are the linear velocity components and angular rates of the fuselage, are the Euler angles, are the flapping angular rates and angles of the four rigid blades, are the lagging angular rates and angles, are the blade tip dynamic torsion states, are the main rotor induced velocities, is the tail rotor induced velocity, as well as and are the delayed fuselage downwash and sidewash states, respectively. is four rotorcraft controls,

where is the collective input, is the lateral input, is the longitudinal input, and is the pedal input.  is the vector of the turbulence disturbances,

where are the turbulence components of the th segment, thblade of the main rotor, are the turbulence components of the fuselage, are the turbulence components of the horizontal stabilator, are the turbulence components of the vertical fin, and are the turbulence components of the tail rotor. represents the time in seconds.

* 1. *Pilot Model*

The widely used compensatory pilot model [40-42] is employed for the simulation in atmospheric turbulence. The lateral axis in Fig. 9 is used to illustrate the design procedure, where and are the trimming values of the roll attitude and lateral velocity,  and are the true errors of the roll attitude and lateral velocity, and are the observed errors by pilot, and represents the rotorcraft flight dynamics model. The pilot models are presented in the dotted box. The pilot model for the roll attitude control is a simplified precision model [43],

where,

is the pilot gain representing pilot’s ability to respond to the error of the roll attitude. It is designed for the desired crossover frequency  of the open-loop system . is a pure time delay to account for the pilot’s cognitive responsiveness. It takes the value of 0.1 s in this research. are the lead and lag time constants of the equalization term which reflects a pilot’s ability to predict a control input and the ease a pilot with to generate the input. The equalization term is designed for the open-loop system behaving like a delayed integrator around the crossover frequency .

are the natural frequency and damping ratio of the neuromuscular system associated with contraction of muscles through which control input is applied by a pilot. The suggested natural frequency is 10 rad/s in Hess’s researches on the structural pilot model [44, 45], accompanied by the desired crossover frequency of 2 rad/s. The suggested damping ratio is 0.707, while proprioceptive feedback is closed to reduce the actual damping ratio to 0.15. In this study, the natural frequency is designed with to achieve a balance between the neuromuscular system serving its function and rejecting the high-frequency disturbance, and the damping ratio is directly set with = 0.15-0.3 in that the precision pilot model does not have proprioceptive feedback.



Fig. 9. Multi-loop compensatory control model of pilot.

The outer-loop pilot model for the lateral velocity control takes the following form,

where is the pilot gain for the desired crossover frequency of the open-loop system . According to the rules for the multi-loop pilot model [46-48], is a good choice.



Fig. 10. Visual model of pilot.

Pilot’s remnants for both inner- and outer-loop controls are simulated with Hess’s visual model [44], as shown in Fig. 10, where is the band-limited white noise with a unit intensity, and are the true and observed values of the error signal, as well as is the shaping filter of pilot’s remnant,

where the time constant is designed withandthe gain is designed withto achieve asignal-to-noise ratio of in the low-frequency range before the cutoff frequency [49].

Pilot models for the other three axes were obtained by repeating the same procedure above. Multi-axis control will lead to high-frequency phase lags and reduction in crossover frequencies [46-48]. In this study, the high-frequency phase lags are considered by increasing the damping ratio of the neuromuscular system. The reduction in crossover frequencies is included by reducing the pilot gains with a dividing factor ,

where represents the variance of band-limited white noise associated with visual cue quality. For multi-axis tasks without visual cue degradation, is dependent on the task interference between different control axes [48],

where is the number of axes being controlled. For this study, , .

The actual value of the inner-loop crossover frequencies for the lateral, longitudinal, and vertical axes is 2.5 rad/s while the crossover frequency for the yaw axis is 2 rad/s to achieve a relaxed position hold (±4.6 m) for a hover task in bluff-body turbulence following the conditions of the flight test in [16]. The pilot models were further designed and scheduled with airspeed from 10-60 m/s in 5 m/s increments to analyze pilot workload variation with different flight conditions in the next section. The practical values for the pilot models in simulations were obtained in real-time by a linear table lookup with airspeed.

* 1. *Validation of Pilot-Model-in-the-Loop Simulation*

The distributed turbulence model and pilot model were validated by comparing the predicted rotorcraft responses and pilot controls with flight test data by a UH-60 rotorcraft hovering on the leeward side of a hangar [16]. The flight condition is with =11.3 m/s at an altitude of 12.2 m to simulate the flight test with the aircraft headed into the wind. The ground effect of main rotor is not considered. The bluff-body turbulence is assumed to be isotropic, and the length scales and intensities are and , respectively. The validated CETI model was also implemented in the flight dynamics model for comparison. The time histories of the rotorcraft responses and pilot controls were then used to calculate the Power Spectral Densities (PSD) for comparison with the flight test data. It is noteworthy that the units for the linear velocities and pilot controls are and in accordance with the flight test data. Furthermore, the PSDs were calculated with the two-sided spectrum.

Figure 11 shows the comparison results of the rotorcraft frequency responses to turbulence. The flight test data are only available for the heave, roll, pitch, and yaw rate responses, and therefore the lateral and longitudinal velocity responses are compared with the CETI model. As observed, both of the proposed distributed model and the CETI model compare well with the flight test data in the frequency range of interest of pilot workload. This suggests that the integrated distributed model and flight dynamics model is accurate for the simulations of rotorcraft operations in atmospheric turbulence. However, some minor differences can be observed between the proposed and CETI models if we look more closely. The distributed model predicts more roll attitude and lateral velocity than the CETI model. Considering that the CETI model was developed from the flight test data at low speed and assumes the same spectrum for the lateral and longitudinal equivalent control inputs of turbulence, it may underestimate the influence of the lateral turbulence for low-speed conditions.

Figure 12 shows the comparison results of the corresponding pilot controls measured in the PSD form. The pilot controls from both turbulence models agree well with the flight test data. The pilot model and flight dynamics model can predict reasonable pilot controls for rotorcraft flight in atmospheric turbulence.

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| 1. Linear velocities | 1. Roll rates |
| Fig. 11 Comparison of rotorcraft frequency response to bluff-body turbulence. | |

The updated distributed model of low-altitude atmospheric turbulence was further validated by comparing the predicted pilot controls with flight test data in free-stream turbulence [50]. The flight test data were recorded via a UH-60 helicopter hovering at 85 m over the taxiway of an airport. The terrain roughness and reference wind speed at 10 m were set to 0.1 m and 5 m/s to simulate the turbulent environment with = 6.82 m/s and =0.46 m/s. The comparison results are shown in Fig. 13 in the PSD form.

It can be seen the predicted pilot controls agree well with the flight test data in the frequency range of 1-10 rad/s. The discrepancies at the high frequencies are due to the inadequacy of the models for pilot’s remnants, but they do not affect the analysis of pilot workload because pilot controls are imposed within frequencies less than 10 rad/s. The pilot-in-the-loop simulation model is appropriate for the analysis of rotorcraft operation in low-altitude freestream turbulence.

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| Fig. 12. Comparison of power spectral densities of pilot controls for rotorcraft flight in bluff-body turbulence. | Fig. 13. Comparison of power spectral densities of pilot controls for rotorcraft flight in freestream turbulence. |

# Effect of Terrain Roughness on Predicted Pilot Workload in Turbulence

The effect of terrain roughness on pilot workload was explored by the simulation of a UH-60 rotorcraft flying in low-altitude atmospheric turbulence. The reference wind speed at the altitude of 10 m is 8 m/s and the terrain roughness of 0.01, 0.1, 1, and 3 m were used to simulate the turbulent environments over short grass, farmland, city centers, and rugged hills, respectively.

Figure 14 shows a comparison of the rotorcraft responses to turbulence. The task is a rotorcraft hovering at the altitude of 10 m with the airspeed of 10 m/s. Figure 15 shows that larger pilot controls are required for the stabilization of the rotorcraft resulting from the increased terrain roughness. This is in line with the increased turbulence intensities with terrain roughness in Fig. 3.

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| 1. Linear velocities | 1. Roll rates |
| Fig. 14. Comparison of rotorcraft frequency responses to turbulence for different terrain roughnesses. | |

The pilot intensity and cutoff frequency from Tischler and Remple [51] are employed for the quantitative analysis of pilot workload,

where is the pilot intensity, is the pilot cutoff frequency, and is the PSD of a pilot control signal.

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| Fig. 15. Comparison of pilot controls in power spectral density for rotorcraft flight in turbulence resulting from different terrain roughnesses. | |

Figures 16 and 17 show the variations of the pilot intensities and cutoff frequencies with altitude and terrain roughness. The reference wind velocity at the altitude of 10 m is 8 m/s. The flight conditions are for the UH-60 rotorcraft hovering in the freestream turbulence of the atmospheric boundary layer. The turbulence intensities and length scales as well as the rotorcraft airspeed are determined by Eqs. (2)-(5).

Figure 16 shows that the pilot intensities of the lateral, longitudinal, and pedal controls increase with terrain roughness but decrease with flight altitude. This is reasonable due to the variation of the turbulence intensities in Fig. 3. However, the pilot intensity of the collective control shows an opposite trend with altitude although it also increases with terrain roughness. This is due to the increment of the turbulent length scales with altitude in Fig. 4. The aircraft behaves more like a point in turbulence with the increasing length scales as the flight altitude increases, which causes more linear velocities and less angular motions.

Figure 17 shows that the pilot’s cutoff frequencies increase with terrain roughness and this trend is more evident for the cases at high altitudes than at low altitudes. This is a combined effect of the increasing freestream velocity and decreasing turbulent length scales with terrain roughness. The trends of the pilot cutoff frequencies with altitude are complex. This is because that the increasing length scales with altitude result in less high-frequency rotorcraft motions for most turbulence conditions, but the increasing wind speed with altitude increases more high-frequency angular motions for the conditions with large terrain roughness and high altitude. Considering all of the results presented in Figs. 16 and 17, the overall pilot workload for a rotorcraft hovering in turbulence increases with the increased terrain roughness and decreased flight altitude.

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| Fig. 16. Variation of pilot intensities with altitude and terrain roughness. | Fig. 17. Variation of pilot cutoff frequencies with altitude and terrain roughness. |

Figures 18 and 19 present the variations of the pilot intensities and cutoff frequencies with airspeed and terrain roughness. The reference wind speed is 8 m/s. The flight conditions are for the UH-60 rotorcraft flying in low-altitude atmospheric turbulence at the altitude of 300 m with the airspeeds of 15-60 m/s by the increment of 5 m/s.

As observed, both pilot intensities and cutoff frequencies increase with airspeed. The increased pilot intensities are due to the increasing dynamic pressures of the rotorcraft aerodynamic surfaces with airspeed [36]. As for the increasing pilot cutoff frequencies, they result from increased turbulence cutoff frequencies. In summary, the pilot workload for a rotorcraft flying in low-altitude turbulence increases with airspeed under the same conditions of turbulent environment and flight altitude.

|  |  |
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| Fig. 18. Variation of pilot intensities with airspeed and terrain roughness. | Fig. 19. Variation of pilot cutoff frequencies with airspeed and terrain roughness. |

# Discussion

Although good progress has been achieved with the release of the latest version of rotorcraft handling qualities performance specification, ADS-33F-PRF [52], there is still a dearth of specific stipulations on turbulence requirements for rotorcraft applications. As a result, the turbulence stipulations from the MIL-F-8785C [20] for fixed-wing aircraft are widely used in rotorcraft research. Compared to fixed-wing aircraft, rotorcraft often encounter more severe turbulence not merely because of the low-altitude flight conditions but also due to the impact of the diverse underlying terrains. In this paper, the result of wind speed with altitude and terrain roughness showed that a rougher terrain could result in a more rapidly increased wind speed with altitude. Besides, the results of turbulence intensities and length scales showed that turbulence over a rougher terrain had larger intensities and smaller length scales than that over a smoother terrain. However, the turbulence stipulations from the MIL-F-8785C only give the statistical properties with altitude as shown in the Appendix, omitting the impact of terrain roughness or only regarding the impact of a specific terrain of airport. In comparison, the proposed low-altitude turbulence model predicted much larger turbulent intensities and smaller length scales over rough terrains, such as farmland, city center, rugged hills, etc., supporting the necessity of a low-altitude turbulence model for rotorcraft applications. As an effort toward this aim, the simulation results of turbulence velocities showed that the proposed model captured the effect of terrain roughness and rotational motions on the turbulence velocities of rotor blade segments.

The effect of terrain roughness on pilot workload for rotorcraft operations in low-altitude turbulence was investigated using pilot-model-in-the-loop simulations. It was shown that the predicted rotorcraft responses and pilot controls in the form of power spectral density were in good agreements with flight test data. The comparisons of rotorcraft responses and pilot controls between different underlying terrains showed that operations over a rougher terrain would result in larger rotorcraft responses and pilot controls. The results of the pilot control intensities and cutoff frequencies with altitude and terrain roughness, as well as with airspeed and terrain roughness, showed that rotorcraft operations over a rougher terrain would result in higher pilot workload with the increments of both pilot intensities and cutoff frequencies for flight at different altitudes and airspeeds. The proposed model of rotorcraft operations in low-altitude turbulence is applicable for rotorcraft handling qualities and pilot workload investigations in low-altitude turbulence over various underlying terrains, and potentially contributes a bit to the establishment of turbulence stipulations for a future rotorcraft handling qualities performance specification.

Future work will continue on this topic to examine the effect of terrain roughness on pilot workload for nap-of-the-earth maneuvers in low-altitude turbulence via offline simulations and pilot-in-the-loop simulations.

# Conclusions

This paper detailed the development of a new low-altitude atmospheric turbulence model. The distributed model was updated and integrated with a UH-60 flight dynamics model and a multi-loop compensatory pilot model. The pilot-model-in-the-loop simulation was validated for rotorcraft operations in bluff-body and freestream turbulence conditions, respectively. Finally, the effect of terrain roughness on pilot workload in turbulence was analyzed quantitatively. The following conclusions were drawn:

1. The roughness of underlying terrains has a significant impact on the low-altitude atmospheric environment. The variation of wind profile with altitude grows more rapidly as the terrain roughness increases. The turbulence intensities increase with both altitude and terrain roughness while the length scales increase with the increment of altitude and the decrement of terrain roughness for the same conditions of the reference wind speed.
2. The pre-warped Tustin transformation approach is accurate for the turbulence modeling over different underlying terrains and the updated distributed model captures the effect of rotational velocities on the turbulence components of main rotor blades.
3. The simulation model can predict rotorcraft responses and pilot controls in both bluff-body and freestream turbulence conditions.
4. The intensities and cutoff frequencies of pilot controls in low-altitude turbulence are affected by the variations of the turbulence intensities, length scales and translational speed with terrain roughness, rotorcraft airspeed, and flight attitude. The corresponding predicted pilot workload increases with the increased terrain roughness and decreased flight altitude, as well as increases with the increased rotorcraft airspeed under the same conditions of the turbulent environment and flight altitude.

# Appendices

According to the MIL-F-8785C, the low-altitude turbulent length scales and intensities up to 1000 *ft* are functions of altitude,

where *,* , are the turbulent length scales, , , are the turbulence intensities, represents the altitude in *ft*, and is the mean wind speed at 20 *ft* above the local terrain.

Typically for light turbulence, the wind speed at 20 *ft* is 15 *knots*; for moderate turbulence, the wind speed is 30 *knots*; and for severe turbulence, the wind speed is 45 *knots*.

# Conflict of Interest Statement

None.

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