

Advanced Pilot Modeling for Prediction of Rotorcraft Handling Qualities in Turbulent Wind[☆]

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Abstract

Turbulent wind is known for potentially deteriorating rotorcraft performance and handling qualities when fulfilling their operation and duties. However, related research is rarely reported and could be possibly attributed to the absence of an effective analytical tool. This paper proposes a pilot model to explore the effect of turbulent wind on rotorcraft handling qualities. It consists of three components: a stabilization control component, a trajectory planning component, and a trajectory tracking component. A slalom task in the turbulent wind is used for the validation of this new pilot model. The simulation results have demonstrated that the new pilot model can not only plan and track a desired trajectory by determining a pilot's guidance strategy, but also predict handling qualities through modelling the effect of the vestibular system. The new pilot model predicts the effect of steady wind component on a pilot's maneuvering aggressiveness and yaw control performance for various ground speeds. It is also capable of predicting the handling qualities in turbulent wind due to increased turbulence intensity and reduced flight control authority.

Keywords: Pilot model; rotorcraft; handling qualities; atmospheric turbulence; flight dynamics

Nomenclature

e_x, e_y = longitudinal and lateral position errors, m

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F_y, F_z	= lateral and vertical forces in body axes, N
g	= gravitational acceleration, m/s^2
h	= flight height, m
k	= coupling constant of tau guidance strategy
K	= control gain
m	= vehicle mass, kg
n	= normal load factor
N_s, N_{trn}	= number of simulations and number of turns of slalom mission task element
t	= time, s
T	= motion duration of tau guidance trajectory, s
u, v, w, p, q, r	= linear velocities and angular rates of rotorcraft in body axes, m/s and rad/s
$U_h, U_{10}, U_{30},$	= steady wind velocity at the height of h m, 10 m, and 30 m, respectively, m/s
v_x, v_y, v_z	= longitudinal, lateral, and vertical velocities in NED axes, m/s
V, V_A	= ground speed and airspeed, m/s
V_W, ψ_W	= steady wind velocity and direction, m/s and deg
x, y, z	= position coordinates in the NED axes, m
$\delta_{\text{col}}, \delta_{\text{lat}}, \delta_{\text{lon}}, \delta_{\text{ped}}$	= collective, lateral, longitudinal stick inputs and pedal input, %
Δt_i	= duration to pass through the i th section of slalom path, s
Δy	= initial gap of tau guidance trajectory, m
$\Delta x_s, \Delta y_s$	= spatial interval between adjacent turns and lateral distance from centerline of slalom path, m
σ_y	= lateral distance standard error, m

σ_w	= vertical turbulence intensity, m/s
τ_y, τ_g	= tau of perceived position gap y and intrinsic tau guide, s
χ, β	= course and sideslip angles, rad
Φ, Θ, Ψ	= Euler angles, rad
ω_c, τ_p	= crossover frequency and preview time of pilot model, rad/s and s

Subscripts

d	= quantity associated with desired trajectory
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Superscripts

.	= derivative
^	= quantity associated with a pilot's proprioceptive system
~	= normalized quantity
', ''	= first- and second-order derivatives of a normalized quantity to the normalized time

Acronyms

HQs	= Handling qualities
HQSF	= Handling-quality sensitivity function
MTE	= Mission task element
NED	= North-East-Down
PSD	= Power spectral densities
SAS	= Stability augmentation system
UCE	= Usable cue environment

1. Introduction

2 Rotorcraft nap-of-the-earth maneuvers especially when encountering turbulent winds are considered demanding tasks.

Under these circumstances, a rotorcraft's response can exhibit high levels of nonlinearity and multi-axis coupling. Maneuvers have to be guided taking full advantage of visual, vestibular, and proprioceptive cues [1-3], but a pilot could be distracted due to extra workload required for disturbance rejection and multi-channel coordination, reducing performance and Handling Qualities (HQs) [4-6]. The effect of turbulent wind on HQs still presents a challenging problem for rotorcraft applications in spite of recent research on turbulence models that have been developed from physics- or data-based modeling methods [7-10]. Piloted flight experiments are expensive, time-consuming, and sometimes high-risk for these multi-cue, multi-channel, and multi-strategy flight tasks. Developing a pilot model is an attractive approach not only for the simulation and HQs prediction of rotorcraft maneuvering flight in turbulent wind but also to reduce time and cost through design and development to certification, training and operations of a prototype rotorcraft [11].

A pilot's control activity can be divided into three functions: stabilization, guidance, and navigation [12]. The first two functions are dominant when performing rotorcraft maneuvering tasks such as Mission Task Elements (MTE) defined in the rotorcraft HQs performance specification ADS-33 [13]. The stabilization, or compensatory function, refers to the pilot's continuous correctional effort to avoid deviating from a desired flight state [14]. It is a relatively high-frequency control activity and has been the most extensively studied [15-23]. Hess [16-17] proposed the structural pilot model for rotorcraft maneuvering simulations, HQs and adverse man-machine coupling prediction, as well as simulator fidelity assessment. The pilot model includes critical elements to simulate proprioceptive, vestibular, and visual systems used by a human pilot when controlling a vehicle. A metric for HQs evaluation, referred as the Handling-Quality Sensitivity Function (HQSF) [16], was calculated from the simulated proprioceptive signals, and thus the HQs could be evaluated for the specific MTEs [17]. Other pilot models have also been developed as well, such as the precision model [24] and optimal control model [25], to simulate a pilot's control behavior for rotorcraft maneuvering flight in a turbulent atmospheric environment. The guidance function is mainly concerned with the avoidance of obstacles [12]. It is essentially a flight-path management activity. Pilot control inputs for this function are made at a lower frequency than for the stabilization function [14]. It was generally modelled by a trajectory planning component and a trajectory tracking component [26]. The trajectory planning component is to plan a desired vehicle trajectory confirming a pilot's guidance strategy while the trajectory tracking component is to control a vehicle to track a desired trajectory. The classical pilot models simulated the trajectory tracking component by closing an outer loop with the errors between the desired positions and velocities and the corresponding aircraft states in addition to the inner-loop stabilization control. Hess's study [27] showed that a pilot could combine the desired future path and the current aircraft states to generate present control inputs to the vehicle to improve flight performance, which is the so-called preview control. Research led by Mulder [28, 29] further demonstrated that humans adapted their feedforward control dynamics to the controlled element dynamics with

preview information of the target trajectory to cancel their own and the controlled element's lags to improve flight performance. As to the trajectory planning component, desired trajectory time histories are usually formulated by a smoothed trajectory using high-order polynomial functions to avoid unrealistic rotorcraft oscillations [30]. Recent researches [31-35] have applied Tau theory to generate a desired trajectory through a tau coupling process using an optic flow parameter tau (τ) from either externally or internally generated motion. The parameter τ is defined as the ratio of instantaneous position gap to velocity [32]. It is essentially the instantaneous time to contact when approaching an object. For rotorcraft maneuvering flight, the pilot would pick up visual information from look-ahead points to form a position gap and thus the tau guidance strategy could be used to adapt to changing cues and task demands for maneuvering flight [33]. The tau guidance strategy has been demonstrated by a variety of piloted simulations, such as helicopter deceleration maneuver and terrain-following flight [34], the landing flare maneuver of fixed-wing aircraft [35], etc.

Classical pilot models generally focused on pilot's stabilization function but not the guidance function, particularly for rotorcraft maneuvering flight. Although significant progress has been made in the development of preview control model [29] and in the use of τ to model a pilot's guidance strategy [3, 14], they rely only on visual cues for guidance. Since the good flight performance for highly aggressive maneuvers needs to depend on making good use of proprioceptive, vestibular, and visual cues as well as multi-channel coordinated compensation, there is a demanding requirement for development of a pilot model, the focus of this paper, combining multi-cue, multi-channel, and multi-strategy control techniques for rotorcraft maneuvering simulation in turbulent wind. The research in this paper will also apply this pilot model to investigate the effect of turbulent wind on rotorcraft maneuvering HQs. Section 2 of this paper will give a brief introduction to the simulation model including a turbulent wind model and a flight dynamics model. Section 3 describes the pilot model sequentially with the control strategy, the stabilization control component, the trajectory tracking component, and the trajectory planning component. Section 4 illustrates the experimental setup for the validation of the proposed pilot model and HQ analysis in turbulent wind. Section 5 presents the methodology for HQs analysis and validates the proposed pilot model for maneuvering flight simulation. In Section 6, the effect of turbulent wind on rotorcraft HQs is investigated from the influence of steady winds and atmospheric turbulence to the assessment of rotorcraft configurations with different Stability Augmentation System (SAS) authorities in turbulent wind environment. Finally, the results are discussed in Section 7 and the conclusions are drawn in Section 8.

2. Simulation Model

Figure 1 shows the simulation scheme for rotorcraft maneuvering flight in turbulent wind. The simulation model in this paper consists of two components: a low-altitude turbulent wind model and a rotorcraft flight dynamics model.

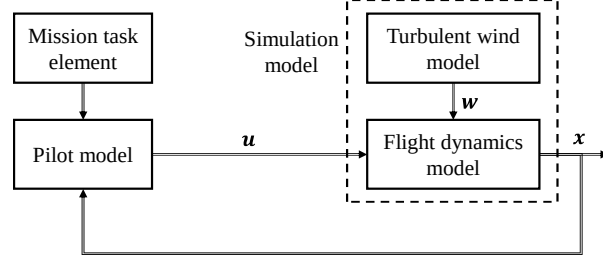


Fig. 1 Simulation scheme for rotorcraft maneuvering flight in turbulent wind

The instantaneous velocity of turbulent wind is formulated with a steady wind velocity and a turbulence velocity. The steady wind velocity is assumed invariable with time and the magnitude is formulated by the power law [36],

$$U_h = U_{10} \left(\frac{h}{10} \right)^\alpha \quad (1)$$

where U_h is the steady wind velocity at the height of h m above the ground, and U_{10} is the steady wind velocity at the height of 10 m. The exponent α is an empirically derived coefficient dependent upon the underlying terrain roughness [37]. The steady wind components are calculated by transforming the steady wind velocity U_h into the North-East-Down (NED) axes with the wind direction angle ψ_w , as shown in Fig. 2.

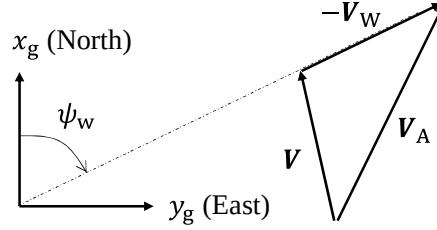


Fig. 2 Relationship among wind speed V_W , aircraft ground speed V and airspeed V_A

The turbulence components are simulated by the distributed turbulence model [8-10] shown in Fig. 3. The atmospheric turbulence field is represented as a control volume of the cuboid $ABCDEFGH$, which covers the whole aircraft and moves together with it. The front surface $ABCD$ sits in front of the main rotor and is perpendicular to the airspeed V_A . The breadth of the rectangle is $2R_T$, the length is L_T , and the height is H_T , where R_T is the radius of the main rotor. White-noise-driven shaping filters for the generation of discrete turbulence components are derived from the one-dimensional von Kármán spectra [38],

$$\begin{cases} \Phi_{uu}(\Omega) = \sigma_u^2 \frac{2L_u}{\pi} \frac{1}{[1 + (aL_u\Omega)^2]^{5/6}} \\ \Phi_{vv}(\Omega) = \sigma_v^2 \frac{L_v}{\pi} \frac{1 + (8/3)(aL_v\Omega)^2}{[1 + (aL_v\Omega)^2]^{11/6}} \\ \Phi_{ww}(\Omega) = \sigma_w^2 \frac{L_w}{\pi} \frac{1 + (8/3)(aL_w\Omega)^2}{[1 + (aL_w\Omega)^2]^{11/6}} \end{cases} \quad (2)$$

1 where $\Phi_{uu}, \Phi_{vv}, \Phi_{ww}$ are the spectra for the longitudinal, lateral, and vertical turbulence components, Ω is the spatial
2 frequency, $\sigma_u, \sigma_v, \sigma_w$ are the standard deviations of the turbulence components, L_u, L_v, L_w are the turbulent length
3 scales, and $a = 1.339$.

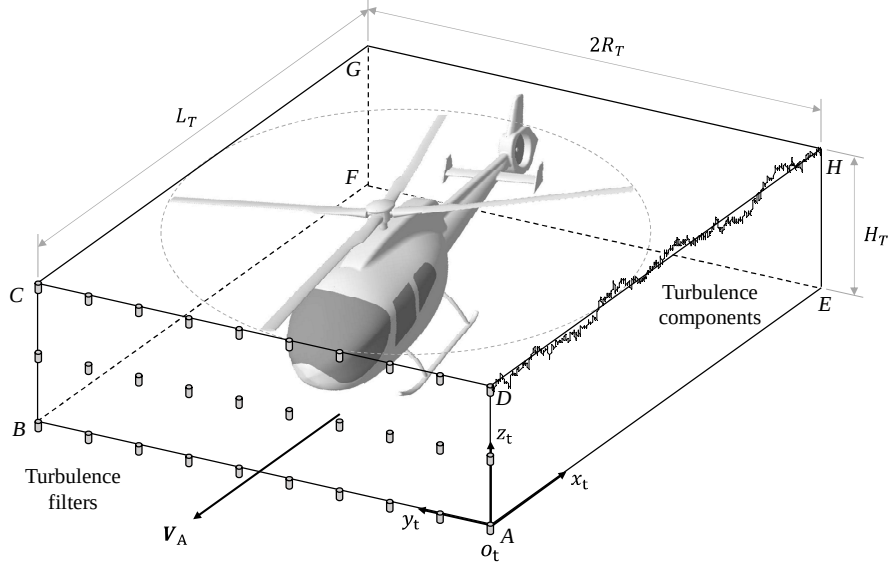


Fig. 3 Distributed turbulence model [10]

A set of the shaping filters are related by a linear transformation with the spatial cross-correlation [38],

$$\begin{cases} R_{uu}(i, j) = \frac{2^{2/3}}{\Gamma(1/3)} \zeta^{1/3} \left[K_{1/3}(\zeta) - K_{2/3}(\zeta) \frac{\xi_2^2 + \xi_3^2}{2aL_u\xi} \right] \\ R_{vv}(i, j) = \frac{2^{2/3}}{\Gamma(1/3)} \zeta^{1/3} \left[K_{1/3}(\zeta) - K_{2/3}(\zeta) \frac{\xi_3^2 + \xi_1^2}{2aL_v\xi} \right] \\ R_{ww}(i, j) = \frac{2^{2/3}}{\Gamma(1/3)} \zeta^{1/3} \left[K_{1/3}(\zeta) - K_{2/3}(\zeta) \frac{\xi_1^2 + \xi_2^2}{2aL_w\xi} \right] \end{cases} \quad (3)$$

where R_{uu}, R_{vv}, R_{ww} are the correlation coefficients between the longitudinal, lateral, and vertical turbulence components of the i th and j th filters. $\xi_1 = |x_i - x_j|, \xi_2 = |y_i - y_j|, \xi_3 = |z_i - z_j|, \xi = \sqrt{\xi_1^2 + \xi_2^2 + \xi_3^2}, \zeta = \xi/(aL)$. x_i, y_i, z_i and x_j, y_j, z_j are the coordinates of the i th and j th filters, Γ is the gamma function, and K is the modified Bessel function of the second kind.

The related filters are placed on the surface $ABCD$ to form the turbulence field. From Taylor's 'frozen field' hypothesis [38], 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 are distributed backward to fill up the turbulence field when the rotorcraft and the cuboid $ABCDEFGH$ are flying forward with the airspeed V_A . Thus, the low-altitude atmospheric turbulence field is formed. The turbulence components at each aerodynamic surface were calculated

with the nearest interpolation to the turbulence field and were summed with the steady wind components for incorporation with the flight dynamics model.

The flight dynamics model used in this paper is a generic UH-60A helicopter as described by Ji et al. [24]. The model is formulated with both rigid body dynamics and high-order main rotor dynamics. A three-state dynamic inflow model is used to simulate the main rotor inflow dynamics. The aerodynamic forces and moments of the main rotor are determined with blade element theory. The airfoil lift and drag coefficients of blade elements are obtained with an interpolation method based on the wind tunnel test data. The main rotor blades are assumed to be rigid bodies. The rigid flapping and lagging motions of each blade are derived from the aerodynamic and inertial moment equilibrium at the hinge. The blade elastic torsional degree of freedom is modeled empirically as a dynamic twist affecting equally each of the rotor blades. The impact of the atmospheric turbulence on the helicopter is considered by superimposing the turbulence wind components directly on the local inflow velocity components of each aerodynamic surface (including main rotor, fuselage, horizontal stabilator, vertical fin, and tail rotor). A SAS was developed that resembles the SAS of the UH-60A helicopter [39]. The SAS functions to provide three-axis rate damping and lagged rate damping (pseudo attitude hold). The control authority of each channel is limited to ± 10 percent of total control travel in pitch, roll, and yaw. The transfer functions for roll, pitch, and yaw channels are given below, respectively,

$$\frac{\delta_{\text{lat}}^{\text{sas}}}{p}(s) = \frac{206.754(s + 1.5704)}{s^3 + 33.1652s^2 + 534.1544s + 520.9001} + \frac{0.278}{s} \% / (\text{deg/s}) \quad (4)$$

$$\frac{\delta_{\text{lon}}^{\text{sas}}}{q}(s) = \frac{307.462(s + 1.1254)}{s^3 + 24.2029s^2 + 298.2384s + 160.9515} \cdot \frac{7s}{7s + 1} \% / (\text{deg/s}) \quad (5)$$

$$\frac{\delta_{\text{ped}}^{\text{sas}}}{r}(s) = \frac{434.5613}{s^2 + 34.3147s + 390.1332} \cdot \frac{2s}{2s + 1} \% / (\text{deg/s}) \quad (6)$$

where $\delta_{\text{lat}}^{\text{sas}}$, $\delta_{\text{lon}}^{\text{sas}}$, and $\delta_{\text{ped}}^{\text{sas}}$ are the SAS control signals for roll, pitch, and yaw channels, and p , q , and r are the roll, pitch, and yaw rates.

The incorporated turbulent wind model and flight dynamics model can be expressed as,

$$\dot{\mathbf{x}} = f(\mathbf{x}, \mathbf{u}, \mathbf{w}, t) \quad (7)$$

where $\mathbf{x}$ is the state vector of motion, $\mathbf{u}$ is a rotorcraft's four conventional cockpit control vector, $\mathbf{w}$ is the turbulence disturbances on the aircraft aerodynamic surfaces.

The incorporated turbulent wind model and flight dynamics model have been widely validated by comparing the trimming results, frequency responses to cockpit controls as well as frequency responses to turbulence against the flight test data. More details about the formulation and validation of the models can be obtained in Refs. [8-9, 24].

3. Pilot Model

3.1 Scheme of Proposed Pilot Model

Figure 4 shows the proposed pilot control strategy. The aircraft angles Φ, Θ, β , angular rates p, q, r , as well as vertical velocity v_z and normal load factor n are employed in the inner-loop stabilization control component to produce the lateral stick input δ_{lat} , longitudinal stick input δ_{lon} , collective stick input δ_{col} , and pedal input δ_{ped} , where Φ and Θ are the roll and pitch angles, β is the sideslip angle, as well as p, q, r are the angular rates in body axes. The stabilization control component also tracking the desired aircraft angles $\Phi_d, \Theta_d, \beta_d$, angular rates p_d, q_d, r_d , as well as vertical velocity v_{zd} and normal load factor n_d for maneuvering simulation. In the outer loop, the trajectory planning and tracking components are combined to model a pilot's guidance function. The trajectory tracking component compares the desired ground velocity V_d , course angle χ_d , and position coordinates x_d, y_d, z_d with the corresponding aircraft states to produce the desired attitudes $\Phi_d, \Theta_d, \beta_d$, angular rates p_d, q_d, r_d , as well as the vertical velocity v_{zd} and normal load factor n_d . Finally, the trajectory planning component provides the desired velocity- and position-time histories following the description of a selected MTE.

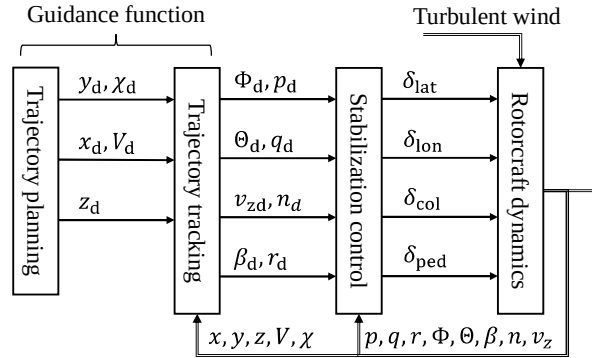


Fig. 4 Control strategy for rotorcraft maneuver in turbulent wind

3.2 Stabilization Control Component

The structural pilot model by Hess [1-2, 16-17] is chosen for stabilization control as it can approximately account for visual, proprioceptive, and vestibular cues which a real pilot will use for stabilization. The structure of the pilot model for roll angle control is illustrated in Fig. 5. A pilot relies mostly on the visual cues to track the desired angle Φ_d . The visual loop deals with the visual tracking error e between the desired roll angle Φ_d and the roll angle Φ of the aircraft through the control gain K_Φ and the time-delay $e^{-\tau s}$ to produce the control signal $\Delta\delta_1$. Pilot's visual error is modelled by the visual model [2] in the dashed box between the visual tracking error e and the control gain K_Φ . The white noise

1 η with the variance σ_η^2 is saturated with the limits $\pm 2\sigma_\eta^2$, multiplies the visual tracking error e , and then is passed
2 through a first-order shaping filter to produce the visual error signal. The quality of visual information sensed by the pilot
3 is quantified by σ_η^2 . An approximate relation between σ_η^2 and the Usable Cue Environment (UCE) ratings defined in the
4 ADS-33E-PRF was suggested in [1-2] as

$$\begin{aligned} 0 \leq \sigma_\eta^2 < 0.1, & \quad \text{UCE} = 1 \\ \text{if } 0.1 \leq \sigma_\eta^2 < 0.2 & \quad \text{UCE} = 2 \\ 0.2 \leq \sigma_\eta^2 < 0.3, & \quad \text{UCE} = 3 \end{aligned} \quad (8)$$

6 In addition to the visual loop, the pilot usually combines the proprioceptive and vestibular loops to improve stability
7 and tracking performance. The proprioceptive and vestibular cues are summed with the weighted coefficients λ_1 and λ_2
8 to establish a roll rate estimate [2], which is passed through the control gain K_p to produce the control signal $\Delta\delta_2$. The
9 proprioceptive signal $\hat{p}$ is produced from the pilot's internal model $\hat{p}/\delta_{\text{lat}}$ while the vestibular signal is sensed directly
10 from motion cues. The desired roll rate p_d is used as a reference for the vestibular signal to enhance the trajectory
11 tracking performance. The control signals $\Delta\delta_1$ and $\Delta\delta_2$ are summed and fed to the neuromuscular system G_{nm} of the
12 pilot and then passed to the cockpit force/feel system G_{fs} to produce the lateral stick input δ_{lat} . The neuromuscular
13 system G_{nm} is modeled as a second-order transfer function by neglecting very high-frequency input information [16],

$$G_{\text{nm}} = \frac{\omega_{\text{nm}}^2}{s^2 + 2\omega_{\text{nm}}\zeta_{\text{nm}}s + \omega_{\text{nm}}^2} \quad (9)$$

15 where ω_{nm} and ζ_{nm} are the natural frequency and damping ratio. The cockpit force/feel system dynamics is selected
16 from Hess's research [17],

$$G_{\text{fs}} = \frac{625}{s^2 + 35.35s + 625} \quad (10)$$

18 The successful implementation of the structural pilot model in Fig. 5 depends upon a sensible selection of pilot
19 parameters. The design rules from Hess [16-17] were widely validated to have the capabilities to match the control
20 behavior of a real pilot in the frequency range of interest of HQs and to perform the required stabilization function.
21 Therefore, Hess's method is taken for the selection of the pilot model parameters. The gain K_p is chosen such that all of
22 the damping ratios of the closed-loop proprioceptive system are larger than 0.15; the gain K_Φ is selected so that the open-
23 loop crossover frequency of the visual system is equal to 2 rad/s, which is a representative value of high-gain pilot control
24 activity derived from flight-test data [17]. The variance of the visual noise σ_η^2 is chosen as 0.1 to achieve a Level-1 UCE.
25 The cognitive delay τ takes a typical value of 0.2 s. A first-order transfer function is obtained for the proprioceptive
26 system using the least-squares approximation to the aircraft dynamics near the region of crossover frequency. The
27 weighted coefficients λ_1 and λ_2 for the roll rate estimate take a 0.75/0.25 split for simulation cases with motion cues

on and take a 1/0 split for cases with motion cues off [2]. The neuromuscular damping ratio ζ_{nm} and natural frequency ω_{nm} are selected as typical values of 0.707 and 10 rad/s [17].

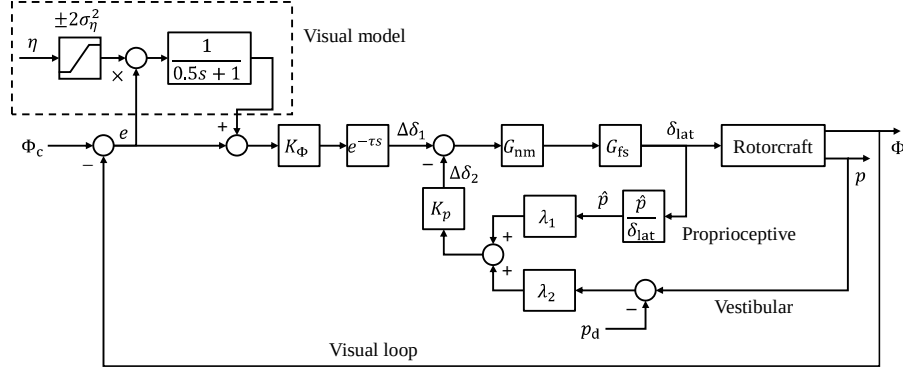


Fig. 5 Structural pilot model for roll angle control [2]

The same procedure is repeated for the longitudinal, heave, and yaw channels. The pitch angle Θ and pitch rate q are taken as the visual and vestibular signals for pitch angle control. The sideslip angle β and heading rate r are used in the yaw axis and the vertical speed v_z and normal load factor n in the vertical axis. The desired visual signals and additive vestibular signals will be obtained from the trajectory tracking component.

3.3 Trajectory Tracking Component

The trajectory tracking component combines preview control and coordinated-turn techniques. The preview control laws combine the current and future values of desired position and velocity as well as the current aircraft position and velocity to produce desired visual signals (attitudes and vertical velocity) for the inner-loop stabilization control component. The turn coordination laws produce desired vestibular signals (angular rates and normal load factor) according to equilibrium in the forces to further improve the tracking performance.

1) Preview Control Laws

The ground velocity V and course angle χ are employed to control the magnitude and direction of the speed vector $\mathbf{V}$, as well as the position coordinates x, y, z are taken as reference signals for position control in the longitudinal, lateral, and vertical axes, respectively. The course angle χ is the direction of the speed vector $\mathbf{V}$ in the horizontal plane and is defined as,

$$\chi = \arctan \frac{v_y}{v_x} \quad (11)$$

where v_x and v_y are the longitudinal and lateral velocity components in the NED axes.

The lateral axis is used to illustrate the development of the preview control laws. Figure 6 shows the preview control law for lateral trajectory tracking, where χ_d and χ are the desired and current course angles, e_y is the lateral position error, τ_p is the pilot preview time, as well as K_χ , K_{χ_p} , and K_y are the control gains. A feedforward preview of the desired course angle is introduced to compensate for the inherent delays in the man/machine system [28]. Furthermore, the lateral position error is also fed back to improve the position tracking precision. The longitudinal and lateral position errors are calculated by,

$$\begin{pmatrix} e_x \\ e_y \end{pmatrix} = \begin{bmatrix} \cos\chi & \sin\chi \\ -\sin\chi & \cos\chi \end{bmatrix} \begin{pmatrix} x_d - x \\ y_d - y \end{pmatrix} \quad (12)$$

where e_x and e_y are the longitudinal and lateral position errors, x and y are the position coordinates of the controlled vehicle in the NED axes, as well as x_d and y_d are the desired position coordinates in the NED axes.

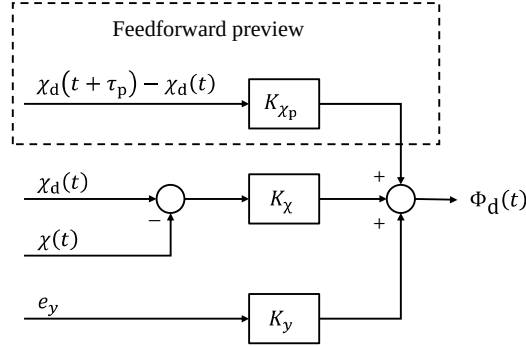


Fig. 6 Preview control law for lateral trajectory tracking

The control law in Fig. 6 is defined for the lateral trajectory tracking,

$$\Phi_d(t) = K_\chi[\chi_d(t) - \chi(t)] + K_{\chi_p}[\chi_d(t + \tau_p) - \chi_d(t)] + K_y e_y \quad (13)$$

where the preview gain K_{χ_p} is chosen as the same as the control gain K_χ for simplicity. As a consequence, the preview control law in Eq. (13) is simplified as,

$$\Phi_d = K_\chi[\chi_d(t + \tau_p) - \chi(t)] + K_y e_y \quad (14)$$

The pilot gain K_χ is designed to obtain the desired crossover frequency $\omega_{c\chi}$ for course angle tracking. According to the rules for multi-loop pilot models [2], $\omega_{c\chi} = 1/3 \omega_{c\Phi}$ is a good rule of thumb. The pilot gain K_y is designed to obtain the desired crossover frequency ω_{cy} for lateral position tracking. The value of ω_{cy} is chosen as 1/5 of $\omega_{c\chi}$. Thus, the preview control law for the lateral trajectory tracking has been formed.

The same procedure is applied on the longitudinal trajectory tracking and the control law is described in Eq. (15) that includes the ground velocity V as the control signal

$$\Theta_d = K_V[V_d(t + \tau_p) - V(t)] + K_x e_x \quad (15)$$

where K_V and K_x are the control gains for ground velocity and position tracking, $V_d(t + \tau_p)$ is the previewed ground speed at the time $t + \tau_p$, as well as $V(t)$ is the aircraft ground speed at the time t .

The pilot control law for the vertical trajectory tracking is,

$$v_{zd} = K_z[z_d(t + \tau_p) - z(t)] \quad (16)$$

where K_z is the pilot gain, $z_d(t + \tau_p)$ is the previewed vertical position at the time $t + \tau_p$, as well as $z(t)$ is the vertical position at the time t .

2) Turn Coordination Laws

To enter a turn from a straight-and-level flight, a human pilot will apply lateral control input in the same direction as the turn [40]. The pedals are only used to compensate for torque to keep the rotorcraft in trim around the vertical axis of the aircraft rather than to assist the turn directly [41]. Keeping the fuselage in the correct trimmed position without sideslip around the vertical axis of the aircraft facilitates the rotorcraft flying forward with the least drag, that is

$$\beta_d = 0 \quad (17)$$

Lateral trim is indicated by a centered ball on a turn and slip indicator to achieve zero sideslip [40]. Recalling the lateral force equation [12],

$$\dot{v} = -ur + wp + g\cos\theta\sin\Phi + \frac{F_y}{m} \quad (18)$$

where g is the gravitational acceleration; F_y is the external lateral force excluding the gravitational force in the body axes; m is the aircraft mass.

Lateral accelerations will provide the pilot with vestibular cues and will become larger as the roll and sideslip angles increase, as indicated in Eq. (18). The pilot corresponds to adopting a control strategy for the coupled yaw to remove the lateral acceleration, that is

$$\dot{v} \approx 0 \quad (19)$$

The vertical velocity w and roll rate p are much smaller compared to the longitudinal velocity u . Therefore, the wp term is negligible when solving the desired yaw rate from Eq. (18), which is,

$$r_d = \frac{1}{u} \left(g\cos\theta\sin\Phi + \frac{F_y}{m} \right) \quad (20)$$

Furthermore, considering a steady level turn with the turn rate $\dot{\Psi}$, the time rate of change of the roll and pitch angles should be zero,

$$\dot{\Phi} = \dot{\Theta} = 0 \quad (21)$$

Thus, the relationship between the fuselage angular rates in the body axes and the time rate of change of the attitude angles is simplified as,

$$\begin{cases} p = -\dot{\Psi}\sin\Theta \\ q = \dot{\Psi}\cos\Theta\sin\Phi \\ r = \dot{\Psi}\cos\Theta\cos\Phi \end{cases} \quad (22)$$

The pitch angle is negligible when solving the desired roll rate, thus

$$p_d = 0 \quad (23)$$

From Eq. (22), the desired pitch rate has the following relationship with the desired yaw rate,

$$q_d = r_d \tan\Phi \quad (24)$$

Since the pilot should remove sideslip in forward flight, the external force F_y is negligible when substituting Eq. (20) into Eq. (24) to solve the desired pitch rate. Therefore, the desired pitch rate for the longitudinal vestibular system is,

$$q_d = \frac{g \cos\Theta \sin\Phi \tan\Phi}{u} \quad (25)$$

Finally, the main rotor force vector will bank during a level turn and as a consequence compensation is required for height hold. Recalling the vertical force equation [12],

$$\dot{w} = uq - vp + g \cos\Theta \cos\Phi + \frac{F_z}{m} \quad (26)$$

where F_z is the vertical force excluding the gravitational component in the body axes.

In view of a steady level-turn flight without sideslip, the term $\dot{w}$ should be zero and both lateral velocity v and roll rate p are so small that the term vp is negligible. Substituting the desired pitch rate q_d , the normal load factor is obtained for the vertical vestibular system,

$$n_d = -\frac{F_{zd}}{mg} = \frac{uq_d}{g} + \cos\Theta \cos\Phi = \frac{\cos\Theta}{\cos\Phi} \quad (27)$$

It can be found that pilots use a combined tracking/compensatory control strategy to achieve a steady coordinated turn in forward flight [42]. The primary control is centered on the lateral axis and the compensation control activities in the other three axes are required to reduce undesired rotorcraft responses suffering from inter-axis coupling and atmospheric disturbances.

3.4 Trajectory Planning Component

The ADS-33 slalom MTE [13], as shown in Appendix A, is taken as an example to present the trajectory planning procedures. The maneuver is started with a constant velocity along a centerline, followed by a series of smooth turns to the left and right in sequence, and is completed by regaining the centerline, as shown in Fig. A1. The τ -theory posits that

a pilot perceives the optic flow parameter τ directly from the looming of objects and surface patterns on the retina for guidance [34]. For the slalom task constraint with the ground speed V_d , the pilot will select the turn ahead as a target once the last turn is passed and will be primarily concerned with the lateral position gap y to complete the maneuver, as shown in Fig. 7. As a consequence, the optical flow information from the lateral position gap is used for guidance. The tau of the lateral position gap τ_y is,

$$\tau_y = \frac{y}{\dot{y}} \quad (28)$$

where $\dot{y} = v_{yd}$ is the closure rate of the lateral position gap.

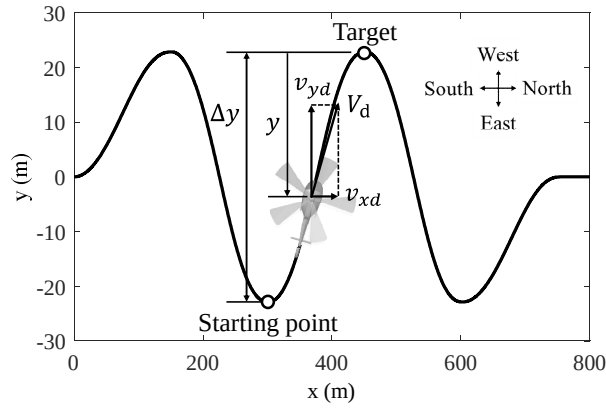


Fig. 7 Target and position gap for tau guidance

According to Lee's study [31], a pilot would guide the motion by coupling its tau onto the intrinsic tau of a second-order bodily motion. An example of bodily motion is electrical charge flowing out of a reservoir of fixed capacity in the body at some controlled (but varying) rate, in which condition the intrinsic tau at any moment was the time-to-being-empty of the reservoir at the current emptying rate. A guide by such a function is referred to as the intrinsic tau guide τ_g . Therefore, the lateral position gap y will be closed by coupling its tau τ_y onto the intrinsic tau guide τ_g , such as

$$\tau_y = k\tau_g \quad (29)$$

where k is the coupling constant. The intrinsic tau guide τ_g can take a number of different forms, but for the case to guide the motion that is approaching the target starting and stopping with zero (lateral) velocity, the most interesting and relevant is the constant acceleration τ_g guide [35]. In Appendix B, the equation for the constant acceleration τ_g guide is derived, together with the equations for the motion tau, the motion gap, the gap closure rate and the rate of change of closure rate that would result from the tau-coupling in Eq. (29). The normalized lateral position, velocity, and acceleration from the constant acceleration τ_g guide are given below,

$$\begin{cases} \tilde{y} = -(1 - \tilde{t}^2)^{\frac{1}{k}} \\ \tilde{y}' = \frac{2}{k} \tilde{t} (1 - \tilde{t}^2)^{\frac{1}{k}-1} \\ \tilde{y}'' = -\frac{2}{k} \left[\left(\frac{2}{k} - 1 \right) \tilde{t}^2 - 1 \right] (1 - \tilde{t}^2)^{\frac{1}{k}-2} \end{cases} \quad (30)$$

where $\tilde{y}$ is the normalized lateral position gap by the initial distance Δy , $\tilde{t}$ is the normalized time by the total motion duration T , $\tilde{y}'$ and $\tilde{y}''$ are the first- and second-derivatives of the normalized gap $\tilde{y}$ to the normalized time $\tilde{t}$.

Inspection of the constant acceleration τ_g guide equations in (30) reveals that the coupling constant k will provide differing responses when approaching a target [35], as shown in Fig. 8. A value of $k < 0.5$ results in an acceleration-deceleration motion with zero residual speed. Furthermore, there are two maximum accelerations during the approaching motion: one is at the beginning to initiate the maneuver and the other is at later to stop it. The first maximum acceleration decreases with the increased coupling constant k . However, the second maximum acceleration decreases with the increment of k when $k < 0.4$, while increases when $k > 0.4$, and achieves a minimum peak value when $k = 0.4$. Since the maximum acceleration decides the aggressiveness of a motion [26], a value of 0.4 is selected as the best for HQs, which was demonstrated by a series of pilot-in-the-loop simulation experiments [32].

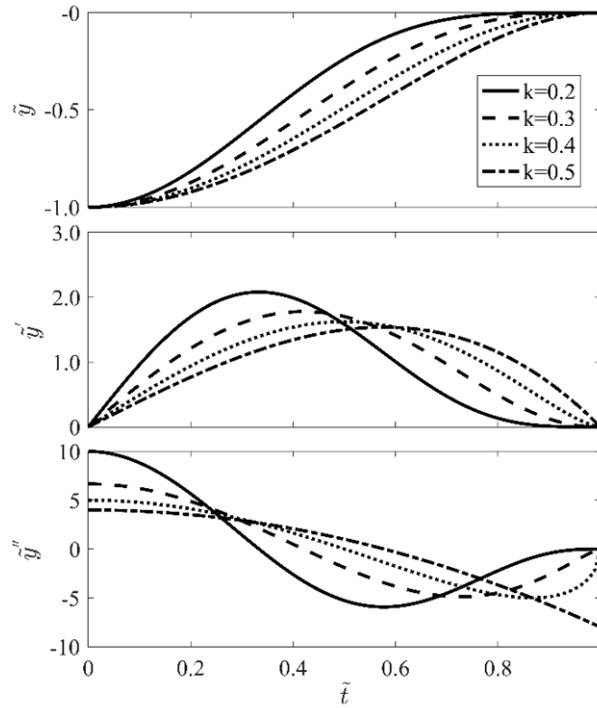


Fig. 8 Gap distance, closure rate and acceleration of constant acceleration guide [35]

The above context gives a piece of lateral trajectory between adjacent turns following the tau guidance strategy. Similarly, every piece of the desired trajectory between adjacent turns can be planned. Supposing the number of the turns to each side of the centerline is N_{trn} , the trajectory can be cut into $2N_{\text{trn}} + 1$ pieces, as shown in Fig. 9. The coordinates

of the i th turn are expressed as (x_i, y_i) and those at the starting and ending locations are (x_0, y_0) and $(x_{2N_{\text{trn}}+1}, y_{2N_{\text{trn}}+1})$, subjective to the following relationship,

$$x_{i+1} = x_i + \Delta x_s \quad (31)$$

$$|y_i| = \Delta y_s \quad (32)$$

where Δx_s is the longitudinal interval between adjacent turns, and Δy_s represents the lateral distance from the centerline.

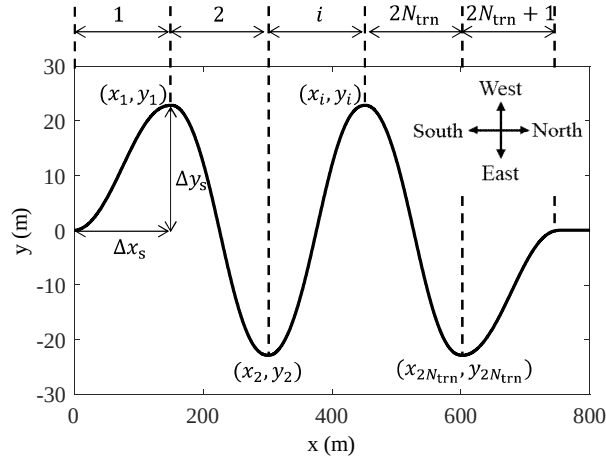


Fig. 9 Flight-path partition for slalom trajectory planning

In view of the desired ground velocity V_d , the duration to pass through the first and last pieces is,

$$\Delta t_1 = \frac{\sqrt{\Delta y_s^2 + \Delta x_s^2}}{V_d} \quad (33)$$

The duration across the other pieces is

$$\Delta t_2 = \frac{\sqrt{(2\Delta y_s)^2 + \Delta x_s^2}}{V_d} \quad (34)$$

Supposing the initial time is t_0 , the time when the aircraft just passing through the i th turn is

$$t_i = \begin{cases} t_0 + \Delta t_1, & i = 1 \\ t_1 + (i-1)\Delta t_2, & i = 2, \dots, 2n_{\text{trn}} \\ t_{2n_{\text{trn}}} + \Delta t_1, & i = 2n_{\text{trn}} + 1 \end{cases} \quad (35)$$

As a consequence, the dimensionless time $\tilde{t}$ during the i th piece is

$$\tilde{t} = \begin{cases} (t - t_i)/\Delta t_1, & t < t_1 \text{ or } t > t_{2n_{\text{trn}}} \\ (t - t_i)/\Delta t_2, & t_1 \leq t \leq t_{2n_{\text{trn}}} \end{cases} \quad (36)$$

According to Eq. (30), the desired lateral velocity v_{yd} for the slalom MTE is,

$$v_{yd} = \dot{y}' \cdot \begin{cases} \Delta y_s/\Delta t_1, & t < t_1 \text{ or } t > t_{2n_{\text{trn}}} \\ -\Delta y_s/\Delta t_2, & t_{2j} < t < t_{2j+1} \\ \Delta y_s/\Delta t_2, & t_{2j+1} < t < t_{2(j+1)} \end{cases} \quad (37)$$

where $j = 1, 2, \dots, n_{\text{trn}}$.

1 Provided with the ground velocity V_d , the desired longitudinal velocity v_{xd} is,

$$2 \quad v_{xd} = \sqrt{V_d^2 - v_{yd}^2} \quad (38)$$

3 Therefore, the desired course angle χ_d is,

$$4 \quad \chi_d = \arctan \frac{v_{yd}}{v_{xd}} \quad (39)$$

5 The slalom MTE requires a constant height, and so the vertical velocity is always zero. Thus, the desired trajectory
6 can be produced by integrating the desired velocities over time.

7 **4. Experimental Setup**

8 The slalom MTE was simulated on the UH-60A helicopter model to validate the pilot model and check the related
9 HQs in turbulent wind. The parameters for the slalom MTE are set following the ADS-33E's requirements as

$$10 \quad \begin{cases} \Delta x_s = 152.4 \text{ m} \\ \Delta y_s = 18 \text{ m} \\ h_d = 30 \text{ m} \end{cases} \quad (40)$$

11 where Δx_s is the longitudinal interval between adjacent turns, Δy_s represents the lateral distance from the centerline,
12 and h_d is the desired flight height.

13 A total number of 15 cases were studied with varied flight conditions, turbulence and wind conditions, as well as
14 different rotorcraft configurations (with SAS on or off). The experimental setup is described as follows.

15 *4.1 Experimental Setup for Validation*

16 Cases 1-3 are simulated in nil wind conditions to validate the proposed pilot model for maneuvering flight, as shown
17 in Table 1. The ground speed is 60 knots complying with ADS-33E's requirements and the number of turns N_{trn} to each
18 side is 8 to achieve a 100-second simulation period for all cases. Both SAS and vestibular cues are off for Case 1, the
19 SAS is off but the vestibular cues are on for Case 2, and both of the SAS and vestibular cues are on for Case 3. The inner-
20 loop crossover frequency for all three cases is 2 rad/s. Trial and error simulations were conducted for each case with τ_p
21 varying from 0 to 2 s with an increment of 0.1 s, and the value to achieve the minimum lateral position tracking error
22 among all of the simulations was chosen as the pilot preview time. The results are 1.7 s, 1.6 s, and 1.5 s for Cases 1-3,
23 respectively.

24 *4.2 Experimental Setup for Analysis in Turbulent Wind*

Cases 4-7 are to check the effect of steady wind on rotorcraft HQs, as shown in Table 2. The wind speed is 15 knots that is a light wind condition defined in the MIL-F-8785C [43]. The wind angles vary among 0 degrees (North wind), 180 degrees (South wind), 90 degrees (East wind), and 270 degrees (West wind) to check the effect of wind direction. The flight speed is 45 knots for Case 4 in headwind, 75 knots for Case 5 in tailwind, and 60 knots for Cases 6 and 7 in sidewind so that the corresponding airspeed reaches the requirement of 60 knots. The number of turns to each side varies among 6, 10, 8, and 8 with the flight speed to achieve a 100-second simulation period for all four cases. The rotorcraft configurations and pilot models are the same for Cases 4-7: the SAS is off, the vestibular cues are on, the inner-loop crossover frequency is 2 rad/s, and the pilot preview time is 1.6 seconds.

Table 1 Experimental setup for validation

No.	Wind & flight	SAS	Vestibular	ω_c (rad/s)	τ_p (s)
1	nil wind	Off	Off	2	1.7
2	$V_d = 60$ kts	Off	On	2	1.6
3	$N_{trn} = 8$	On, 20%	On	2	1.5

Table 2 Experimental setup for analysis in steady wind

No.	U_{30} (kt)	ψ_w (deg)	V_d (kt)	N_{trn}	SAS and pilot model
4	15	0	45	6	SAS off
5	15	180	75	10	vestibular cues on
6	15	90	60	8	$\omega_c = 2$ rad/s
7	15	270	60	8	$\tau_p = 1.6$ s

Cases 8-11 in Table 3 are to investigate the effect of atmospheric turbulence on rotorcraft HQs with the wind speed 15 knots. The wind direction is 0 degrees (North wind) for Cases 8 and 9 and 180 degrees (South wind) for Cases 10 and 11. The vertical turbulence intensity varies from 0.7 to 1.2 m/s by the underlying terrain roughness of 0.1 and 1 m, respectively. The ground speed is 45 knots for Cases 8 and 9 to achieve the airspeed of 60 knots, and the ground speed is 60 knots for Cases 10 and 11 to achieve the airspeed of 45 knots. The number of turns to each side varies from 6 to 8 with the flight speed. The rotorcraft configuration and pilot model are set with the same conditions as Cases 4-7.

Table 3 Experimental setup for analysis in turbulent wind

No.	U_{30} (kt)	ψ_w (deg)	σ_w (m/s)	V_d (kt)	N_{trn}	SAS and pilot model
8	15	0	0.7	45	6	SAS off
9	15	0	1.2	45	6	vestibular cues on
10	15	180	0.7	60	8	$\omega_c = 2$ rad/s
11	15	180	1.2	60	8	$\tau_p = 1.6$ s

Cases 12-15 investigate the effect of the SAS authority on rotorcraft HQs in turbulent wind conditions, as presented in Table 4. The wind speed is 15 knots and the vertical turbulence intensity is 1.2 m/s by the underlying terrain roughness

of 1 m. The wind direction is 0 degrees (North wind) for Cases 12 and 13 and 180 degrees (South wind) for Cases 10 and 11. Correspondingly, the ground speed is 45 knots for Cases 8 and 9 to achieve the airspeed of 60 knots and 60 knots for Cases 10 and 11 to achieve the airspeed of 45 knots. The number of turns to each side varies from 6 to 8 with the flight speed. The SAS authority is 10% for Cases 12 and 14 as well as 20% for Cases 13 and 15. The pilot model is set with the vestibular cues for all cases. The inner-loop crossover frequency is 2 rad/s and the pilot preview time is 1.5 s.

Table 4 Experimental setup for analysis with different SAS authorities

No.	$U_{30}(\text{kt})$	$\psi_w(\text{deg})$	$\sigma_w(\text{m/s})$	$V_d(\text{kt})$	N_{trn}	SAS authority	Pilot model
12	15	0	1.2	45	6	10%	vestibular cues on $\omega_c = 2 \text{ rad/s}$ $\tau_p = 1.5 \text{ s}$
13	15	0	1.2	45	6	20%	
14	15	180	1.2	60	8	10%	
15	15	180	1.2	60	8	20%	

5. Validation of Pilot Model

The proposed pilot model is validated in this Section through linear and nonlinear simulations of the slalom MTE for Cases 1-3. The tracking performance for each case is quantified by defining the standard error $\sigma_{\Delta y}$ between the simulated and desired lateral distances at the turning points,

$$\sigma_{\Delta y} = \sqrt{\frac{1}{N_s \cdot 2N_{\text{trn}}} \sum_{i=1}^{N_s} \sum_{j=1}^{2N_{\text{trn}}} (y_{i,j} - \Delta y_s)^2} \quad (41)$$

where N_s is the number of simulations for each case; $y_{i,j}$ is the distance from the centerline at the j th turn of the i th simulation. Since the lateral distance is set to 18 m as shown in Eq.(40), only a 3-meter margin is left to reach the desired lateral distance (at least 15 m). Therefore, the lateral distance standard error should be smaller than 1 m for the normal-distributed tracking errors to meet the desired lateral distance.

The Handling-Quality Sensitivity Function (HQSF) by Hess [16] is used to predict the HQs levels,

$$\text{HQSF} = \frac{1}{K_e} \left| \frac{U_M}{C} (j\omega) \right| \quad (42)$$

where $C = \Phi_d, \Theta_d, \beta_d, v_{zd}$ represents the desired roll, pitch, sideslip angles, or vertical velocity sensed by pilot's visual system for roll, pitch, yaw, or vertical velocity control; $U_M = \hat{p}, \hat{q}, \hat{r}, \hat{n}$ represents the roll, pitch, yaw rates, or normal load factor sensed by the proprioceptive system; $K_e = K_\Phi, K_\Theta, K_\beta, K_{v_z}$ represents the visual control gain for the four channels. Hess postulates that a pilot's perception of a vehicle's HQs is dependent upon the power of the perceived motion rate by the proprioceptive system. Moreover, Eq. (42) is normalized by the visual control gain to remove the effect of control sensitivity and then the magnitude is referred as the HQSF.

The HQSF can be easily obtained for a linear flight dynamics model [17]. It can be expanded to HQs evaluation for nonlinear simulation by three steps. First, a large number of simulations (100 simulations for research in this paper) are conducted for each case. Then, the Power Spectral Densities (PSD) of the visual tracking and proprioceptive signals are calculated for each simulation and the results are summed and averaged for each case to remove randomness due to pilot's visual error and turbulence disturbance. Finally, the averages of the PSDs are used to calculate the HQSF by Eq. (42).

Figure 10 shows the HQs results from the linear flight dynamics model. HQs (Case 1) for the four control channels are Level 2 (Lateral), Level 3 (Longitudinal), Level 1 (Vertical), and Level 3 (Yaw), resulting in Level-3 HQs for the bare-frame aircraft due to the poorest results in the longitudinal and yaw channels. Compared to Case 1, Case 2, with the vestibular cues, shows better results in all four channels and achieves Level-2 HQs. This is due to less time is required for a pilot to perceive vehicle rate responses from a combination of the vestibular and visual cues than the only visual cues. This effectively reduces the time delay and improves the crossover frequency for the man/machine system [4]. As a result, the increased system stability and control bandwidth improve the HQs level [3]. Furthermore, a comparison between Cases 2 and 3 reveals that the SAS significantly improves the HQs to Level 1 in all channels.

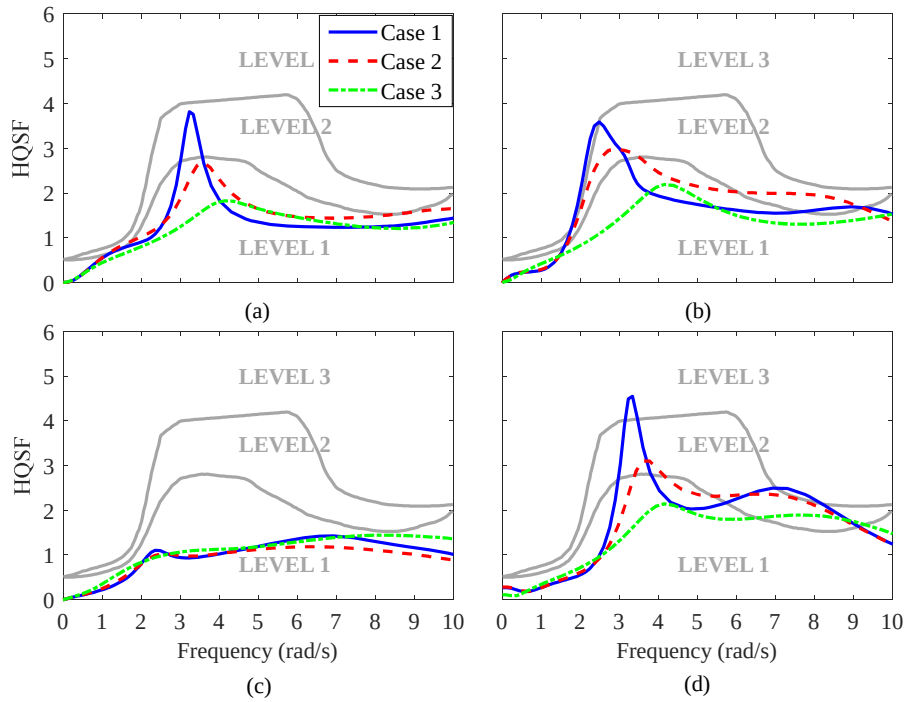


Fig. 10 Handling qualities results by linear flight dynamics model. (a) lateral; (b) longitudinal; (c) vertical; (d) yaw. Gray curves represent boundaries that divide the Level 1, 2, and 3 areas

Figure 11 compares the simulated flight paths using the nonlinear flight dynamics model and the lateral distance standard errors estimated by Eq. (41) among Cases 1-3. The desired flight path is well programmed without abrupt bursts and tracked by the proposed pilot model following the tau guidance strategy. A slight improvement in the tracking

1 performance is shown in Case 2 when the vestibular system is enabled, as explained above due to the larger bandwidth
 2 [3]. Furthermore, Case 3 shows that the SAS helps the pilot achieve the desired tracking performance.

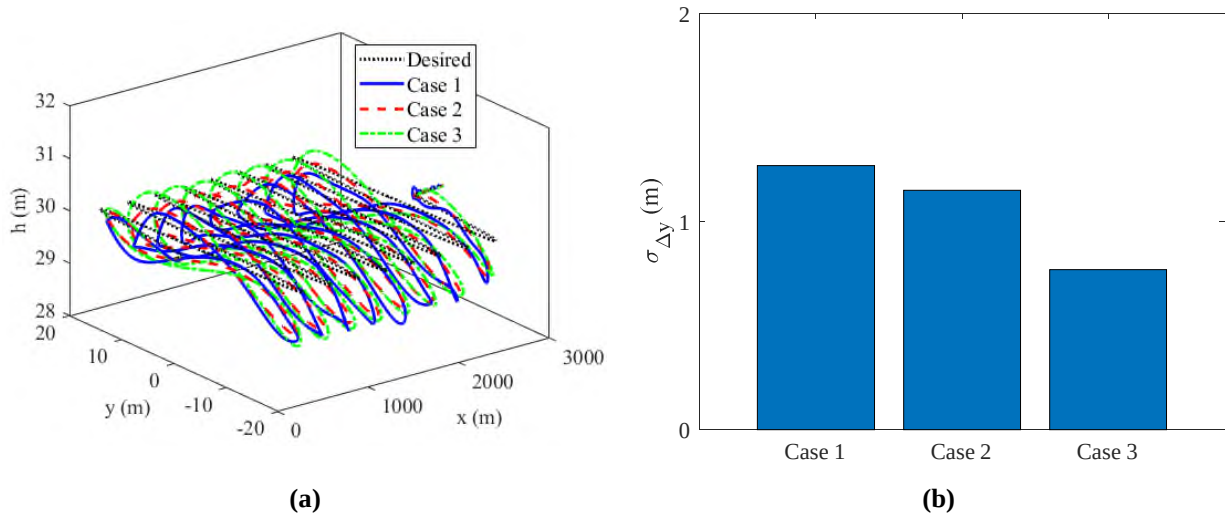


Fig. 11 Comparison of (a) simulated flight path and (b) lateral distance standard error

4 Figure 12 illustrates the visual tracking and proprioceptive signals from the proposed pilot model by nonlinear
 5 simulations. Case 1 shows when the vestibular system is not included, the proprioceptive signals are oscillating around 3
 6 rad/s. In comparison, the 3-rad/s oscillations in the proprioceptive signals are suppressed by the vestibular system in Case
 7 2, demonstrating that the proposed pilot model simulates the improved stability in the man/machine system by the
 8 vestibular system. Case 3 demonstrates that the SAS assists the pilot model to stabilize the man/machine system.

9 Figure 12 further reveals the pilot control strategy for the slalom MTE. The visual tracking and proprioceptive signals
 10 for the lateral channel are much larger than those for the longitudinal, vertical, and yaw channels, since this is a lateral
 11 control dominant tracking task and the pilot relies on the lateral motion cues to accomplish this task [41]. The results also
 12 demonstrate that there are no obvious deficiencies in the aircraft dynamics of the longitudinal, vertical, and yaw axes.
 13 Therefore, lateral control plays the leading role when a pilot rates the HQs level for the UH-60A helicopter flying a slalom
 14 MTE while the other channels are secondly important to coordinate with the primary control [42].

15 The simulated lateral HQSFs by the nonlinear flight dynamics model were calculated by Eq. (42) among Cases 1-3
 16 and the results are shown in Fig. 13. The lateral HQs are Level 2 when the vestibular loop is not closed and are improved
 17 to Level 1 when both the vestibular system and SAS are enabled. The results have a good agreement with the analytical
 18 results in Fig. 10(a) and the desired tracking performance in Fig. 11.

1 The HQs are predicted to Level 2 for the UH-60A bare-frame configuration and Level 1 for the augmented
2 configuration due to the improved effect of the vestibular system and SAS, indicating the accuracy of the pilot model for
3 HQs prediction.

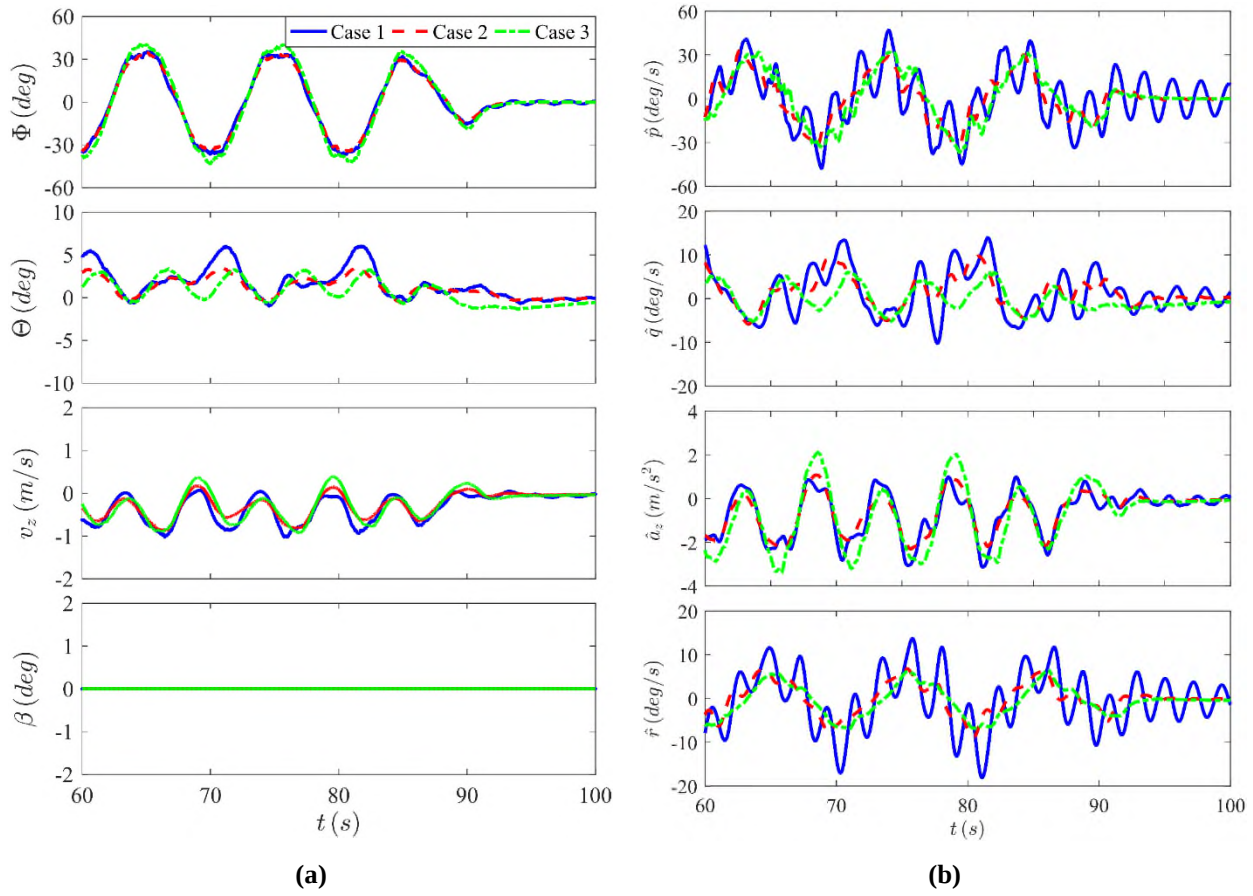


Fig. 12 Visual tracking (a) and proprioceptive (b) signals for HQs evaluation

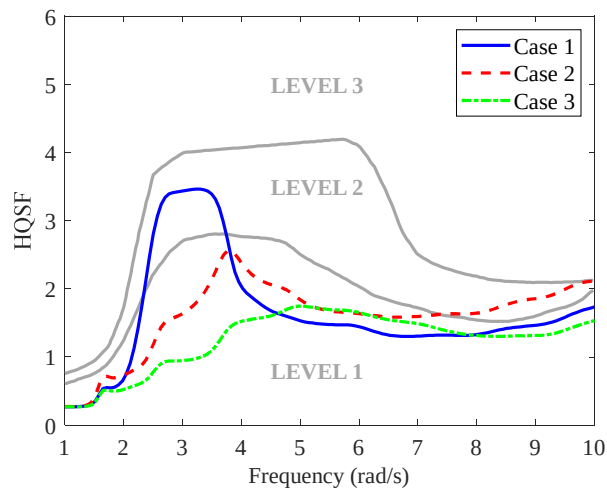


Fig. 13 Comparison of simulated lateral HQSF

6. Handling Qualities Analysis in Turbulent Wind

In this Section, the Slalom MTE is simulated using the nonlinear flight dynamics model for Cases 4-15 and the corresponding lateral HQSFs are calculated to show the effect of turbulent wind on the HQs. The results are given here.

6.1 Effect of Steady Wind

Figure 14 reveals the effect of steady wind on the simulated flight path and lateral distance standard error for Cases 4-7. Compared with Case 2 in nil wind conditions as shown in Fig. 11, the East wind results in the worst tracking performance, the South wind results in the second worse performance, the West wind has nearly no effect, and the North wind improves the performance. The North and South wind results match well with the ground speed varying from 45 knots to 75 knots (as shown in Table 2) in that the trajectory is tracked less aggressively by a smaller ground speed. The East wind is opposite to the direction of the tail rotor thrust and makes the helicopter tend to turn right resulting in a right shift on the flight path, as shown in Fig. 14(a). The West wind is along with the direction of tail rotor thrust and makes it easier for the yaw control.

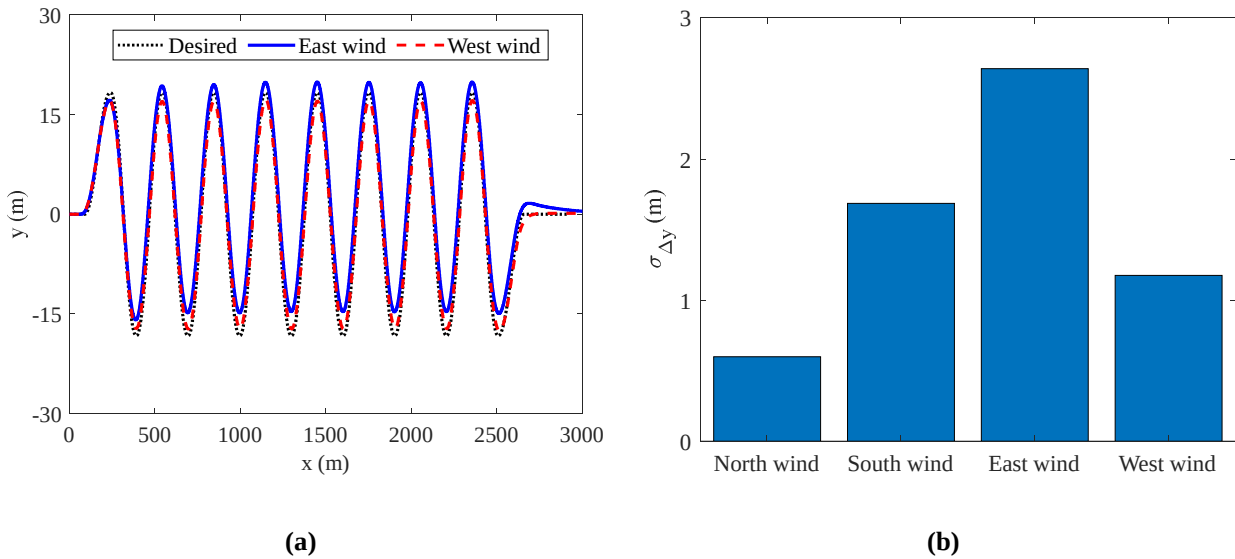


Fig. 14 Effect of steady wind on (a) simulated flight path and (b) lateral distance standard error

Figure 15 shows the effect of steady wind on the lateral HQSFs. Compared to the nil wind condition, the North and East winds have nearly no effect on the HQs. The predicted operation in South wind is much more aggressive resulting in a worse HQSF than that in North wind. The East wind makes it harder for yaw operation and results in a bit worse lateral HQSF than that in West wind in that the East wind is opposite to the direction of the tail rotor thrust while the West wind comes in the same direction as the tail rotor thrust.

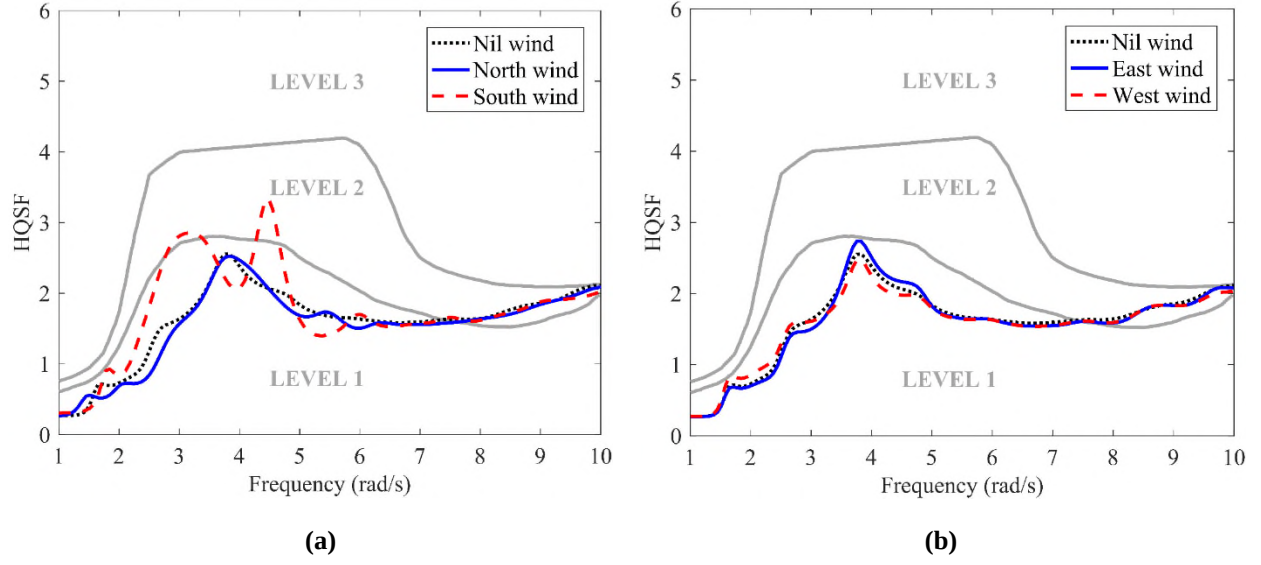


Fig. 15 Effect of steady wind on lateral HQSF

6.2 Effect of Atmospheric Turbulence

Figure 16 shows the effect of atmospheric turbulence on the flight path from Cases 8-11. It can be observed that compared with Fig. 14, the turbulence disturbances increase the lateral distance errors. The errors for North and South wind conditions increase as well with the increased turbulence intensities.

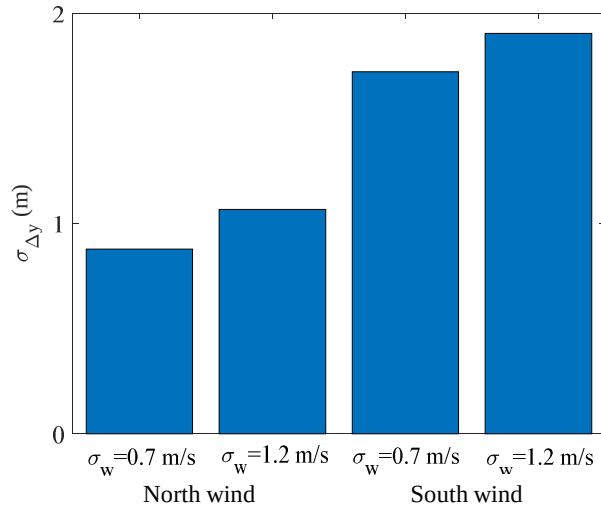
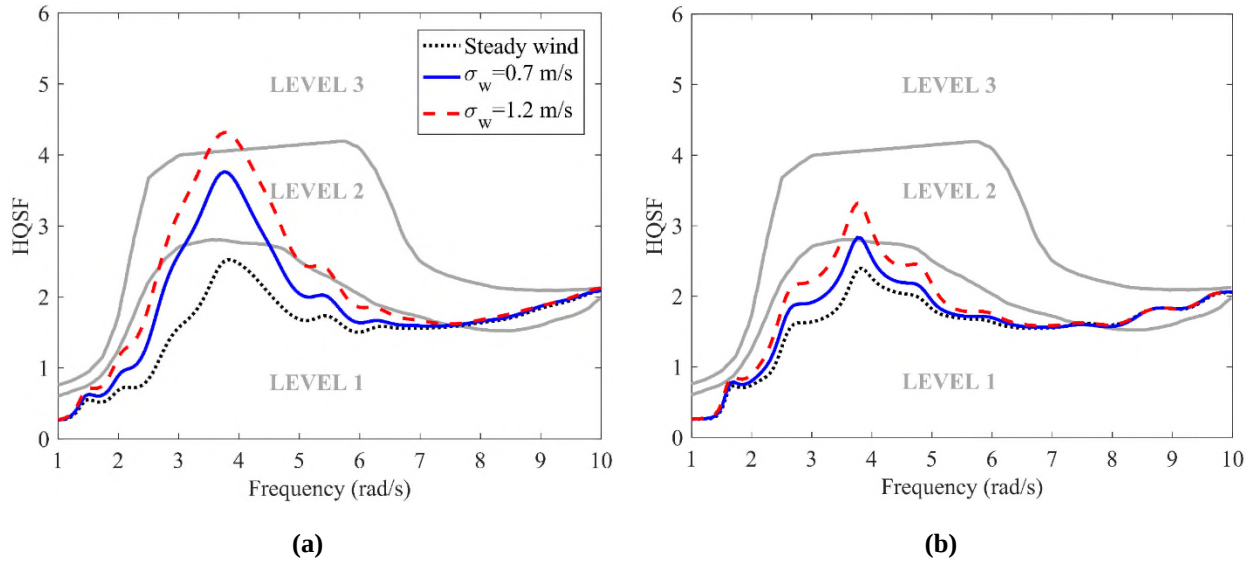


Fig. 16 Effect of atmospheric turbulence on lateral distance standard error

The corresponding lateral HQSFs are compared in Fig. 17. It can be found that atmospheric turbulence significantly increases the lateral HQSFs in the medium-frequency components with the increased turbulence intensity compared with the same wind conditions without turbulence. Fig. 17(b) shows the lateral HQs deteriorate with the increased turbulence intensity. However, the HQs in South wind conditions with the wind speed 15 knots and the ground speed 60 knots are

1 better than those in North wind conditions with the wind speed 15 knots and the ground speed 45 knots, indicating that
 2 rotorcraft HQs are more sensitive to the effect of turbulent wind at low speeds than at high speeds.



3 **Fig. 17 Effect of atmospheric turbulence on lateral HQSF in (a) North wind and (b) South wind**

4 6.3 Effect of SAS Configuration

5 Figure 18 shows the effect of the SAS configuration on the lateral distance standard error for Cases 12-15. Compared
 6 with the same turbulent wind conditions in Fig. 16, the SAS helps the pilot achieve the desired tracking performance for
 7 the North wind cases as the lateral standard error is reduced from 1.1 m/s to 0.8 m/s. The result at the South wind condition
 8 with 20%-authority SAS is also improved with the error reduced from 1.9 m/s to 1.3 m/s. However, the South wind case
 9 with 10%-authority shows poor performance as the error is increased from 1.3 m/s to 1.8 m/s. This can be explained by
 10 the required flight control outputs in Fig. 19, which are significantly increased to a larger level when the ground speed
 11 increases from 45 to 60 knots. The 10%-authority is inadequate for the pilot to complete the maneuver as aggressively as
 12 with a ground speed up to 60 knots, degrading the rotorcraft performance and HQs.

13 Figure 20 presents the corresponding lateral HQSFs and reveals the effect of the SAS configuration on the HQs. The
 14 20%-authority SAS significantly improves the HQs from Level 3 to Level 1 for the North wind cases and from Level 2
 15 to Level 1 for the South wind cases. Furthermore, compared with the 20%-authority cases in South wind condition, it is
 16 evident that the reduced authority deteriorates the HQs although they are still in the Level 1 region.

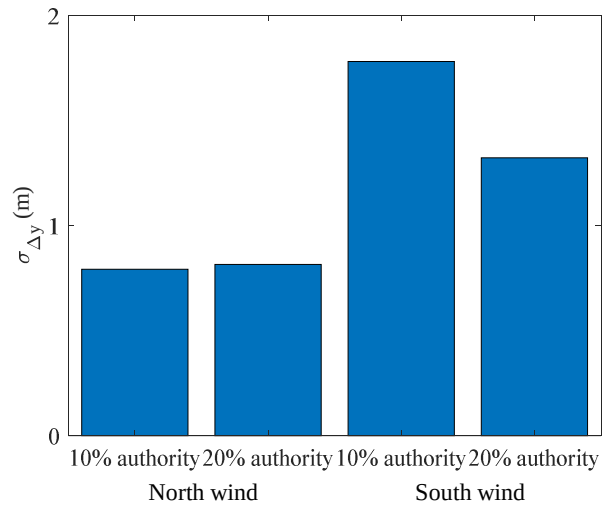


Fig. 18 Effect of SAS configuration on lateral distance standard error

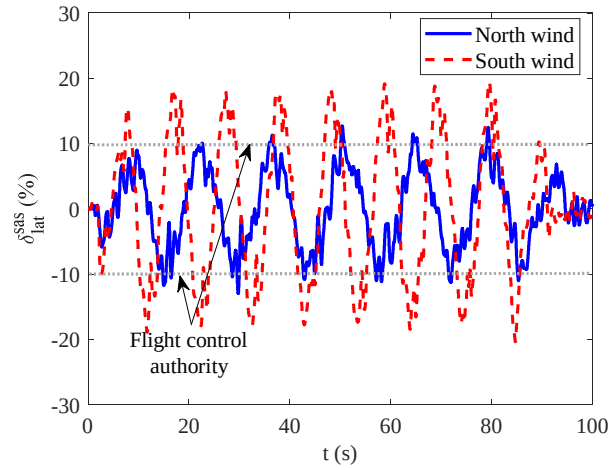
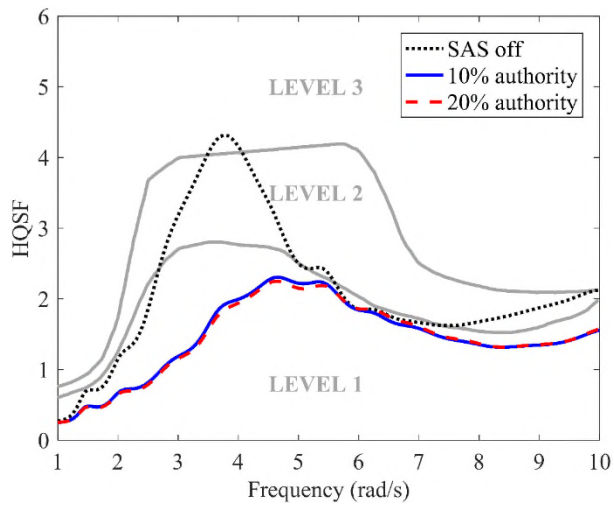
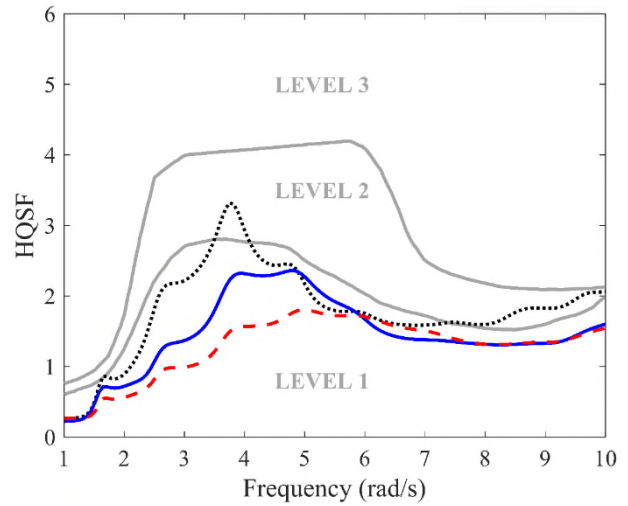


Fig. 19 Effect of turbulent wind on required flight control outputs



(a)



(b)

Fig. 20 Effect of SAS configuration on lateral HQSF in (a) North wind and (b) South wind

1 **7. Discussion**

2 State-of-the-art pilot models for HQs investigations require trajectory planning and tracking conforming to the
3 guidance strategy of a human pilot. Recent progress in preview control behavior [28-29] and bio-inspired optical flow
4 theory [14, 32] from piloted experiments provide a good opportunity to satisfy this kind of requirement. The proposed
5 pilot model has shown that it can predict HQs capturing the effect of the vestibular system and SAS. The nonlinear
6 simulation results demonstrate that it can plan and track a desired trajectory conforming to pilot's tau guidance strategy.
7 Analysis of the visual tracking and proprioceptive signals revealed that the primary tracking-control channel was
8 dominant for the HQs of a maneuvering flight while the other channels employ a compensatory control strategy to reject
9 the inter-axis coupling responses and atmospheric disturbances and were secondly important for the HQs. This work gives
10 an attempt to improve the structural pilot model with a tau guidance law and a preview control strategy for maneuvering
11 flight simulations, providing a convenient desktop tool for rotorcraft HQs investigation.

12 The effect of turbulent wind on rotorcraft HQs was investigated via simulation of the slalom MTE. The comparison
13 between cases in steady wind conditions showed that a headwind could improve the tracking performance and HQs by
14 reducing the ground speed, and tailwind, in contrast, significantly deteriorated the task. Side wind opposite to the direction
15 of tail rotor thrust would lead to a lateral shift from the desired path, which could be trimmed out, however, at the expense
16 of extra pilot efforts. The comparison between cases in turbulent wind conditions showed that atmospheric turbulence led
17 to deteriorated tracking performance and HQs with an increase in turbulence intensities, as expected. The simulation
18 results for the rotorcraft with different SAS authorities revealed that the SAS could help a pilot improve the tracking
19 performance and HQs in turbulent wind. However, the saturation due to the inadequate authority (as shown in Fig. 19)
20 can deteriorate rotorcraft performance and HQs for aggressive maneuvers in turbulent winds as the ground speed was up
21 to 60 knots. The ultimate aim is to establish turbulence stipulations for the next version of ADS-33.

22 **8. Conclusions**

23 This paper developed a pilot model for predicting rotorcraft performance and HQs when maneuvering in turbulent
24 winds. The following conclusions can be drawn upon the investigations.

- 25 1) The proposed pilot model can plan and track a desired trajectory conforming to the tau guidance strategy and the
26 predicted HQs capture the effect of the vestibular system and SAS at a good level.
- 27 2) The pilot control activities from the primary tracking-control channel are dominant in the HQs while the other
28 channels are secondly important for the HQs using a compensatory control strategy to reject the inter-axis coupling
29 responses and atmospheric disturbances.

3) Atmospheric turbulence deteriorates the performance and HQs with increased turbulence intensities. Flight control systems, as simple as a SAS with adequate authority, can significantly improve the tracking performance and HQs in turbulent wind, but not with inadequate authority.

Appendix A: Description of Slalom MTE

The slalom MTE [13] was selected for the maneuvering flight simulation and HQs investigation. It is intended to check the lateral-directional coordination during an aggressive maneuver in forward flight with respect to cones on the ground. The task consists of a series of smooth turns at 500-ft (approximately 150 m) intervals at the reference height of 100 ft (approximately 30 m), as shown in Fig. A1. The runway is from South to North. The turns are at least twice to each side of the course and 50 ft (approximately 15 m) towards West and East from the centerline, with the maximum lateral error of 50 ft (approximately 15 m). The desired performance requires an airspeed of at least 60 knots (approximately 30 m/s) throughout the course and the adequate performance is at least 40 knots (approximately 20 m/s).

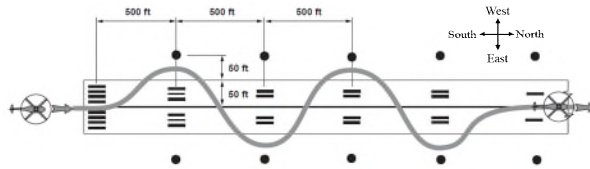


Fig. A1 Suggested course for slalom MTE [13]

Appendix B: Derivation of Constant Acceleration τ_g Guide

Supposing a bodily motion for intrinsic tau guide has an initial motion gap x_{g0} which is closed with the initial closure rate v_{g0} and the constant acceleration a_g , the motion can be described by

$$\begin{cases} \dot{x}_g = v_{g0} + a_g t \\ x_g = x_{g0} + v_{g0} t + \frac{1}{2} a_g t^2 \end{cases} \quad (B1)$$

In view that the closure rate $\dot{x}_g$ is zero at the beginning of the motion and the gap x_g is zero at the end of the motion after the duration T seconds, such as

$$\begin{cases} \dot{x}_g|_{t=0} = 0 \\ x_g|_{t=T} = 0 \end{cases} \quad (B2)$$

With the constraints in Eq. (B2), the acceleration is solved

$$a_g = -\frac{2x_{g0}}{T^2} \quad (B3)$$

Substituting Eq. (B3) into Eq. (B1), the motion equations are simplified as

$$\begin{cases} \dot{x}_g = -\frac{2x_{g0}}{T^2}t \\ x_g = x_{g0}\left[1 - \left(\frac{t}{T}\right)^2\right] \end{cases} \quad (B4)$$

Thus, the intrinsic tau τ_g can be obtained

$$\tau_g = \frac{x_g}{\dot{x}_g} = -\frac{T^2 - t^2}{2t} \quad (B5)$$

If a vehicle under motion to close a gap y is coupled onto the constant acceleration τ_g guide as

$$\tau_y = k\tau_g \quad (B6)$$

Substituting Eq. (B5) into Eq. (B6), it can be obtained

$$\frac{y}{\dot{y}} = -k \frac{T^2 - t^2}{2t} \quad (B7)$$

where y is the motion gap with the initial value $-\Delta y$, and $\dot{y}$ is the closure rate of the motion gap y .

Integrating Eq. (B7) with respect to time successively yields

$$y = -\Delta y \left[1 - \left(\frac{t}{T}\right)^2\right]^{\frac{1}{k}} \quad (B8)$$

To normalize Eq. (B8), define $\tilde{t} = t/T$ and $\tilde{y} = y/\Delta y$, giving

$$\tilde{y} = -(1 - \tilde{t}^2)^{\frac{1}{k}} \quad (B9)$$

The normalized closure rate $\tilde{y}'$ and acceleration $\tilde{y}''$ are

$$\tilde{y}' = \frac{d\tilde{y}}{d\tilde{t}} = \frac{2}{k} \tilde{t} (1 - \tilde{t}^2)^{\frac{1}{k}-1} \quad (B10)$$

$$\tilde{y}'' = \frac{d^2\tilde{y}}{d\tilde{t}^2} = -\frac{2}{k} \left[\left(\frac{2}{k} - 1\right) \tilde{t}^2 - 1 \right] (1 - \tilde{t}^2)^{\frac{1}{k}-2} \quad (B11)$$

Finally, the normalized motion tau $\tilde{\tau}_{\tilde{y}}$ is

$$\tilde{\tau}_{\tilde{y}} = \frac{\tau_y}{T} = \frac{k}{2} \left(\tilde{t} - \frac{1}{\tilde{t}} \right) \quad (B12)$$

Conflict of interest statement

None.

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3 **References**

- 4 [1] R. A. Hess, W. Siwakosit, Assessment of flight simulator fidelity in multiaxis tasks including visual cue quality, *Journal of*
5 *Aircraft*, 38(4) (2001) 607–614.
- 6 [2] R. A. Hess, F. Marchesi, Analytical assessment of flight simulator fidelity using pilot models, *Journal of Guidance, Control, and*
7 *Dynamics*, 32(3) (2009) 760-770.
- 8 [3] L. Lu, M. Jump, Multiloop pilot model for boundary-triggered pilot-induced oscillation investigations, *Journal of Guidance,*
9 *Control, and Dynamics*, 37(6) (2014) 1863-1879.
- 10 [4] D. T. McRuer, E. S. Krendel, Mathematical models of human pilot behavior, Technical Report AGARDograph AG-188, AGARD,
11 1973.
- 12 [5] R. A. Hess, Rotorcraft handling qualities in turbulence, *Journal of Guidance, Control, and Dynamics*, 18(1) (1995) 39-45.
- 13 [6] H. Ji, R. Chen, L. Lu, M. D. White, Pilot workload investigation for rotorcraft operation in low-altitude atmospheric turbulence,
14 *Aerospace Science and Technology*, 111 (2021) 106567.
- 15 [7] J. A. Lusardi, M. B. Tischler, C. L. Blanken, S. J. Labows, Empirically derived helicopter response model and control system
16 requirements for flight in turbulence, *Journal of the American Helicopter Society*, 49(3) (2004) 340-349.
- 17 [8] H. Ji, R. Chen, P. Li, Distributed atmospheric turbulence model for helicopter flight simulation and handling-quality analysis,
18 *Journal of Aircraft*, 54(1) (2017) 190-198.
- 19 [9] H. Ji, R. Chen, P. Li, Distributed turbulence model with accurate spatial correlations for simulation of helicopter flight in
20 atmospheric turbulence, *Journal of the American Helicopter Society*, 64 (2019) 042011.
- 21 [10] H. Ji, R. Chen, P. Li, Real-time simulation model for helicopter flight task analysis in turbulent atmospheric environment,
22 *Aerospace Science and Technology*, 92 (2019) 289-299.
- 23 [11] N. Cameron, M. D. White, G. D. Padfield, L. Lu, D. Agarwal, A. W. Gubbels, Rotorcraft modeling renovation for improved
24 fidelity, in: Vertical Flight Society 75th Annual Forum, Philadelphia, USA, 2019.
- 25 [12] G. D. Padfield, *Helicopter Flight Dynamics: The Theory and Application of Flying Qualities and Simulation Modelling*, John
26 Wiley & Sons, 2008, Chapter 3.
- 27 [13] Anon., *Handling Qualities Requirements for Military Rotorcraft*, ADS-33E (PRF), 2000.
- 28 [14] L. Lu, M. Jump, G. D. Padfield, Development of a generic time-to-contact pilot guidance model, *Journal of Guidance, Control,*
29 *and Dynamics*, 41(4) (2018) 904-915.
- 30 [15] D. T. McRuer, W. F. Clement, P. M. Thompson, R. E. Magdaleno, Minimum flying qualities volume II: pilot modelling for
31 flying qualities application, Technical Report WRDC-TR-9-3100, Flight Dynamics Lab., Air Force Systems Command, Wright–
32 Patterson AFB, 1990.

- [16] R. A. Hess, Unified theory for aircraft handling qualities and adverse aircraft-pilot coupling, *Journal of Guidance, Control, and Dynamics*, 20(6) (1997) 1141-1148.
- [17] R. A. Hess, Y. Zeyada, R. K. Heffley, Modeling and simulation for helicopter task analysis, *Journal of the American Helicopter Society*, 47(4) (2002) 243-252.
- [18] M. D. Pavel, M. Jump, B. Dang-Vu, et al., Adverse rotorcraft pilot couplings—past, present and future challenges, *Progress in Aerospace Sciences*, 62 (2013) 1-51.
- [19] G. Quaranta, P. Masarati, J. Venrooij, Impact of pilots' biodynamic feedthrough on rotorcraft by robust stability, *Journal of Sound and Vibration*, 332(20) (2013) 4948-4962.
- [20] A. Lampton, D. H. Klyde, Power Frequency: A metric for analyzing pilot-in-the-loop flying tasks, *Journal of Guidance, Control, and Dynamics*, 35(5) (2012) 1526-1537.
- [21] R. Takase, J. O. Entzinger, S. Suzuki, Pilot-in-the-loop simulation of simple adaptive fault-tolerant controller, *Aerospace Science and Technology*, 106 (2020) 106125.
- [22] S. Xu, Y. Wu, Modeling multi-loop intelligent pilot control behavior for aircraft-pilot couplings analysis, *Aerospace Science and Technology*, 112 (2021) 106651.
- [23] L. Wang, C. Lu, H. Liu, T. Yue, Method of predicting nonlinear pilot-induced oscillations due to flight control degradation based on digital virtual flight, *Aerospace Science and Technology*, 116 (2021) 106871.
- [24] H. Ji, R. Chen, P. Li, Rotor-state feedback control to alleviate pilot workload for helicopter shipboard operations, *Journal of Guidance, Control, and Dynamics*, 40(12) (2017) 3088-3099.
- [25] D. Lee, N. Sezer-Uzol, J. F. Horn, L. N. Long, Simulation of helicopter shipboard launch and recovery with time-accurate airwakes, *Journal of Aircraft*, 42(2) (2005) 448-461.
- [26] D. Thomson, R. Bradley, Inverse simulation as a tool for flight dynamics research—principles and applications, *Progress in Aerospace Sciences*, 42(3) (2006) 174-210.
- [27] R. A. Hess, K. Chan, Preview control pilot model for near-earth maneuvering helicopter flight, *Journal of Guidance, Control, and Dynamics*, 11(2) (1988) 146-152.
- [28] K. van der El, D. M. Pool, H. J. Damveld, M. R. M. van Paassen, M. Mulder, An empirical human controller model for preview tracking tasks, *IEEE Transactions on Cybernetics*, 46(11) (2005) 2609-2621.
- [29] K. van der El, D. M. Pool, M. R. M. van Paassen, M. Mulder, Effects of preview on human control behavior in tracking tasks with various controlled elements, *IEEE Transactions on Cybernetics*, 48(4) (2017) 1242-1252.
- [30] D. G. Thomson, R. Bradley, Mathematical definition of helicopter maneuvers, *Journal of the American Helicopter Society*, 42(4) (1997) 307-309.
- [31] D. N. Lee, Guiding movement by coupling taus, *Ecological Psychology*, 10(3) (1998) 221-250.
- [32] G. D. Padfield, The tau of flight control, *The Aeronautical Journal*, 115(117) (2011) 521-556.

- 1 [33] G. D. Padfield, M. D. White, Measuring simulation fidelity through an adaptive pilot model, *Aerospace Science and Technology*,
2 9(5) (2005) 400-408.
- 3 [34] G. D. Padfield, G. Clark, A. Taghizad, How long do pilots look forward? prospective visual guidance in terrain-hugging flight,
4 *Journal of the American Helicopter Society*, 52(2) (2007) 134-145.
- 5 [35] M. Jump, G. D. Padfield, Investigation of the flare maneuver using optical tau, *Journal of Guidance, Control, and Dynamics*,
6 29(5) (2006) 1189-1200.
- 7 [36] J. O. Counihan, Adiabatic atmospheric boundary layers: a review and analysis of data from the period 1880–1972, *Atmospheric*
8 *Environment*, 9(10) (1967) 871-905.
- 9 [37] G. Gualtieri, Surface turbulence intensity as a predictor of extrapolated wind resource to the turbine hub height, *Renewable*
10 *Energy*, 78 (2015) 68-81.
- 11 [38] B. Etkin, *Dynamics of Atmospheric Flight*, John Wiley and Sons, Inc., New York, USA, 1972, Chapter 13.
- 12 [39] J. J. Howlett, UH-60A black hawk engineering simulation program, Technical Report NASA CR-166309, 1981.
- 13 [40] Anon., *Helicopter Flying Handbook (FAA-H-8083-21B)*, United States Department of Transportation, Federal Aviation
14 Administration, Oklahoma, 2019, Chapter 2.
- 15 [41] D. Agarwal, L. Lu, G. D. Padfield, M. D. White, N. Cameron, Rotorcraft lateral-directional oscillations: the anatomy of a nuisance
16 mode, *Journal of the American Helicopter Society*, 66 (2021) 042000.
- 17 [42] W. A. Memon, M. D. White, G. D. Padfield, N. Cameron, L. Lu, Helicopter handling qualities: a study in pilot control
18 compensation, *Aeronautical Journal*, 2021, in print.
- 19 [43] Anon., *Flying Qualities of Piloted Airplanes*, MIL-F-8785C, 1980.



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