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Rotorcraft Handling Qualities in Turbulence

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Rotorcraft are often required to perform tasks in environments where atmospheric disturbances can significantly affect performance and vehicle handling qualities. Establishing requirements for rotorcraft handling qualities in turbulence is thus of prime importance, particularly to the military. An analytical study is described that addresses this issue. First, a simplified approach to modeling the aerodynamic effects of turbulence on rotorcraft is presented. A structural pilot model employing a handling-qualities sensitivity function is next used to quantify handling qualities. Next, an hypothesis regarding the manner in which turbulence affects vehicle handling qualities is proposed. Finally, an example of the analytical approach is presented involving the longitudinal hover task of an AH-1G rotorcraft. In addition to the unaugmented vehicle, three levels of stability augmentation are considered, each involving different levels of feedback to achieve their goals.

Nomenclature

p	$= d\phi/dt$, rad/s
q	$= d\theta/dt$ rad/s
r	$= d\psi/dt$, rad/s
u	$= x$ body-axis component of velocity, m/s
v	$= y$ body-axis component of velocity, m/s
w	$= z$ body-axis component of velocity, m/s
w_g	= turbulence vertical velocity, m/s
$\dot{w}_g$	= turbulence derivative m/s
δ_{A_p}	= pilot/SAS lateral cyclic input, cm (at pilot's hand)
δ_{B_p}	= pilot/SAS longitudinal cyclic input, cm
δ_{C_p}	= pilot collective input, cm
δ_{P_p}	= pilot pedal input, cm
θ	= pitch attitude, rad
ϕ	= roll attitude, rad
ψ	= yaw attitude, rad

I. Introduction

THE environment in which rotorcraft are required to operate can amplify the importance of atmospheric disturbances as regards task performance and vehicle handling qualities. For example, low-speed, nap-of-the-Earth rotorcraft flight occurs well within the atmospheric boundary layer where atmospheric turbulence induced by local terrain and man-made structures can adversely affect task performance and even flight safety.

The present document summarizing handling-qualities requirements for military rotorcraft (ADS-33C)[1] approaches the turbulence response problem by simply requiring that the control system bandwidth for disturbances injected at the actuators be identical to that for pilot inputs at the cockpit manipulator and that this bandwidth exceed specified values. Essentially, this mandates that, if necessary, acceptable handling qualities should be obtained through the use of stability augmentation systems (SASs) that rely upon response or output feedback rather than upon command-shaping filters that operate only upon pilot inputs. This requirement was adopted for ADS-33C for two reasons: 1) the flight control systems that formed the data base for the current bandwidth requirement used output feedback and 2) some flight test results with the XV-15 tiltrotor aircraft indicated that command-shaping SASs that provided level 1 handling qualities in still air degraded to level 2 in turbulence.[2]

More recently, flight tests involving the National Research Council of Canada NAE Bell 205 Airborne Simulator suggested that rotorcraft handling qualities for hovering and landing tasks in turbulence were not markedly affected by variation in the disturbance rejection characteristics of the SAS.[3] This would suggest that the requirements of Ref. 1 may be overly restrictive in demanding that acceptable rotorcraft handling requirements be achieved through feedback SAS design.

With the preceding situation serving as a backdrop, an analytical study was undertaken with the following overall goals: 1) to review the current turbulence modeling techniques as regards their applicability to low-speed rotorcraft handling-qualities studies and 2) to shed some light on the manner in which atmospheric turbulence affects vehicle handling qualities.

II. Background

Theories for vehicle handling qualities have not always successfully accommodated the effects of atmospheric turbulence, whether for fixed-wing or rotary-wing vehicles. It has been demonstrated in early flight and simulation studies for both types of vehicles that turbulence intensity and spectrum can have as significant an effect on vehicle handling qualities as the vehicle dynamics themselves.[4,5] Thus, approaches to the specification of vehicle handling qualities that focus upon open-loop vehicle dynamics are not likely to capture the dependence of vehicle handling qualities upon turbulence intensity and spectrum.

The apparent necessity of moving beyond open-loop, vehicle-centered approaches in analytical handling-qualities investigations led to the development of closed-loop, pilot-model-centered approaches.[6–9] In one way or another, these approaches were able to reflect the effects of disturbance characteristics upon vehicle handling qualities.

Of particular interest is the work of Smith,[7] who, more than any other of the "closed-loop school," proposed a theory for handling qualities that was not attached to any particular pilot model. Smith proposed that, in any closed-loop tracking task such as attitude regulation in turbulence, *rate* control activity is of fundamental importance from the standpoint of pilot control and perceived vehicle handling qualities. Hess[10] used Smith's fundamental idea about the importance of rate control and formulated what he called a structural pilot model. It is this model and associated handling-qualities sensitivity function (HQSF) that will form the basis of the rotorcraft handling-qualities study to follow. Before this can be done, however, some discussion of the aerodynamic modeling of turbulence effects on low-speed rotorcraft flight is necessary.

III. Rotorcraft Turbulence Modeling

Any analytical approach to the problem of rotorcraft handling qualities in turbulence requires a realistic but tractable model of the disturbance in question. Most studies involving fixed-wing aircraft can employ Taylor's hypothesis[11] wherein a "frozen" turbulence field is employed. The aircraft, with a velocity considerably larger

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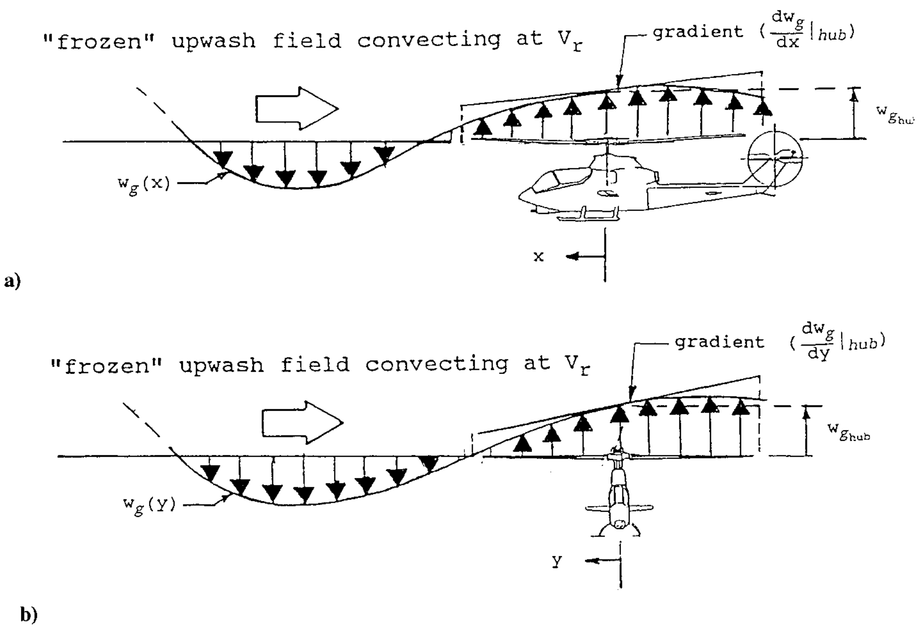

Fig. 1 Simplified turbulence modeling.

than the root-mean-square (rms) turbulence velocities at any point, moves through the frozen field. The three mutually perpendicular turbulence velocities can be one-, two-, or three-dimensional functions of spatial displacement from the origin of the frozen field. Since the aircraft aerodynamic surfaces are (assumed) rigid, they move with the aircraft and their orientations and velocities are identical to those of a body-fixed axis system.

As is the case with most comparisons between fixed- and rotary-wing vehicles, things are not as simple in the treatment of rotorcraft turbulence, particularly at low speed. The legitimacy of the frozen-field hypothesis becomes considerably more tenuous, as does the body-fixed approach for determining aerodynamic forces and moments. This problem was first discussed in some detail by Skelton[12] in relation to V/STOL but not rotary-wing aircraft. A number of more recent studies have been directed toward modeling the effect of turbulence on rotating helicopter blades in forward flight.[13–16] The resulting descriptions, based as they are on blade-centered rather than body-centered axes, require frequency-time representation such as cyclo-stationary random processes. Obviously, the descriptions are quite complex. Although such descriptions may prove very useful for future flight simulation applications and for analytical prediction of gust loads, aeroelastic and vibration problems, etc., they are probably too complex and unwieldy for handling-qualities investigations.

For the sake of simplicity and tractability, the present study will extend the frozen turbulence modeling approach used in fixed-wing studies. The vehicle aerodynamic data to be used in the analysis to be described was taken from Ref. 17. The data in this reference consist of aerodynamic data to be used in obtaining linear dynamic models of a series of rotorcraft. Turbulence inputs are included in the form of linear and angular (rotary) velocity perturbations entering in the aerodynamic terms in the equations of motion, much as in the case of fixed-wing vehicles.[18] However, in Ref. 17, the rotary gust terms were equivalent to aerodynamic damping and did not include the effects of the turbulence gradient upon the response of the rotor tip path plane. The aerodynamic effects of turbulence upwash field gradients, for example, are significantly different for rotorcraft than for fixed-wing vehicles.[19]

Figure 1 shows a hovering rotorcraft exposed to a pair of one-dimensional frozen upwash fields convecting at velocity V_r to the vehicle. Because of the response of the rotor tip path plane, the spatial gradient of the *longitudinal* upwash field shown in Fig. 1a will produce significant *rolling* moments on the vehicle. Likewise, the spatial gradient of the *lateral* upwash field shown in Fig. 1b will produce significant *pitching* moments on the vehicle.[19]

The manner in which the aerodynamic moments just described were approximated in this study can be described by referring to Fig. 1b. First, the turbulence field over the rotor was approximated as a constant ($w_{g_{\text{hub}}}$) and a gradient ($dw_g/dy|_{\text{hub}}$). Thus, the spatial gradient of the turbulence field at the rotor hub was considered to exist over the entire rotor plane. Next, in terms of the effect of the gradient only, the spatial distribution of vertical turbulence velocities was treated as an equivalent cyclical change in the angle of attack experienced at each spanwise station of each rotor blade as it passed through the field. Next, the angle-of-attack variation experienced at the midspan of each rotor blade as it passed through the field was used to calculate an equivalent *longitudinal* cyclic input that was a linear, proportional function of $\dot{w}_g = dw_g/dt$ and included as such in the linear vehicle model. The forces/moments produced by the constant $w_{g_{\text{hub}}}$ were included just as in Ref. 17, by additive perturbations $(w - w_g)$ in the aerodynamic terms of the linear vehicle model.

In formulating pertinent system transfer functions, a value of V_r is needed. This value is not entirely arbitrary here. As in any application of the frozen-turbulence hypothesis, V_r and L_w determine the temporal break frequency of the disturbance spectrum. That is, the temporal break frequency is given by $2V_r/L_w$ rad/s. In terms of handling-qualities investigations, one should focus upon spectra with relatively large break frequencies, i.e., between 0.1 and 1 rad/s. However, because of the manner in which the turbulence aerodynamics are modeled, the majority of power in the turbulence field should derive from spatial wavelengths that are large as compared to the rotor diameter. Obviously, a trade-off is required.

The power spectral density for the turbulence field is given by[16]

$$\Phi_{w_g w_g}(\Omega) = \frac{\sigma_w^2 L_w}{1 + \left(\frac{1}{2}L_w\Omega\right)^2} \tag{1}$$

where $2L_w = L = 88$ m is the characteristic length (approximately eight times the rotor radius of a large rotorcraft such as the CH-53[17]) and $1/\pi L_w = 1/138.3$ cycles/m is the break frequency. Selecting $V_r = 15$ m/s and $L_w = 44$ m yields a temporal break frequency of 0.68 rad/s. At this value, the spatial wavelength is 10.3 times the AH-IG's rotor diameter of 13.4 m. In terms of a trimmed hover condition, the V_r value is large, but not unreasonably so. Thus, the requirements outlined in the preceding paragraph can be assumed to be satisfied. As indicated below Eq. (1), $2L_w$ was based upon the rotor radius of a large rotorcraft. It is common for the atmospheric boundary layer to exhibit turbulence scale lengths ($2L_w$ for vertical

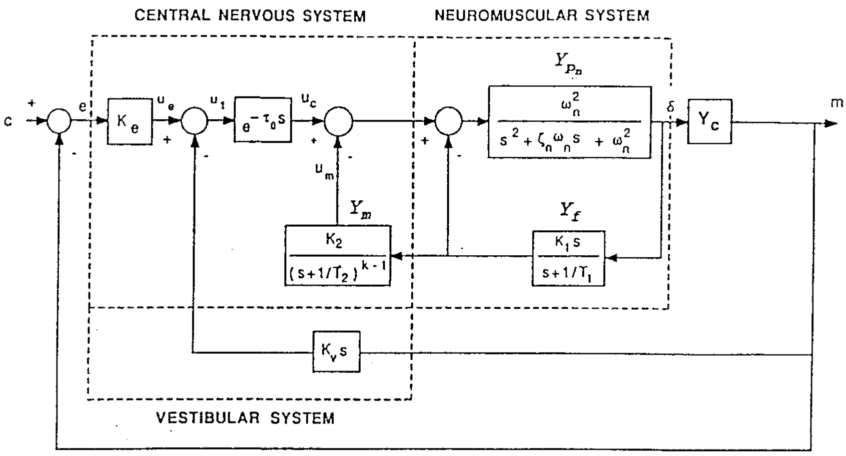

Fig. 2 Structural model of human pilot.

turbulence) of the same order of magnitude as the rotor radius for many medium and large helicopters.[15]

The author is well aware of the oversimplifications inherent in the aerodynamic modeling just described. This approach should be viewed as a *first-order correction* to the manner in which the aerodynamic forces and moments due to turbulence were handled in Ref. 17. It is perhaps worth re-emphasizing at this juncture that this study is focused upon the effects of flight control system characteristics (i.e., those of the SAS) upon handling qualities in turbulence. It is not aimed at determining gust loads, studying turbulence-induced vibration, etc. Thus, the simplified aerodynamic modeling approach used here was deemed adequate.

IV. Pilot Modeling

Primary Loop

In modeling manual control activity in multivariable tasks, one can treat the human as a multi-input, multi-output (MIMO) compensator or as a single-input, single-output (SISO) compensator operating in a nested-loop structure.[20] With the SISO approach, and considering the control of any specific degree of freedom such as the longitudinal motion of a hovering rotorcraft, one can identify a *primary manual control loop*. This is one involving direct manipulative inputs by the human to control a specific output or response variable.[10,21,22] The primary loop serves to stabilize the vehicle and, through its closure, to provide suitable *effective vehicle dynamics* for closure of an outer loop(s) with minimum compensation. Modeling manual control in this fashion, of course, is equivalent to the design of inanimate controllers through sequential loop closure techniques.[23]

The selection of the primary control loop and associated feedback variable in the pilot/vehicle analysis of any flight task parallels what the control system designer would select for an inanimate controller with the same limitations as the human. Space does not permit a detailed discussion of the selection procedure here. Suffice to say that, in the task to be studied (longitudinal position control of a hovering rotorcraft), vehicle pitch attitude can serve as the primary control loop feedback variable.

Structural Model

The model of the human controller in the primary control loop in this study will be the structural model of the human.[10] This model and its genesis have been discussed in the literature quite extensively and will only be described briefly here. Figure 2 shows the structural model. In essence the model assumes that proprioceptive feedback through the elements Y_f and Y_m enable the human to develop the compensation (lead, lag, proportional) needed in the control of the primary-loop variable according to the dictates of the crossover model of the human pilot.[24]

The model of Fig. 2 appears to be seriously overparameterized. However, it has been shown that, for pilot/vehicle analyses such as that which is the subject of this work, most of the model parameters can be set to "nominal" values.[10] The remaining parameters are

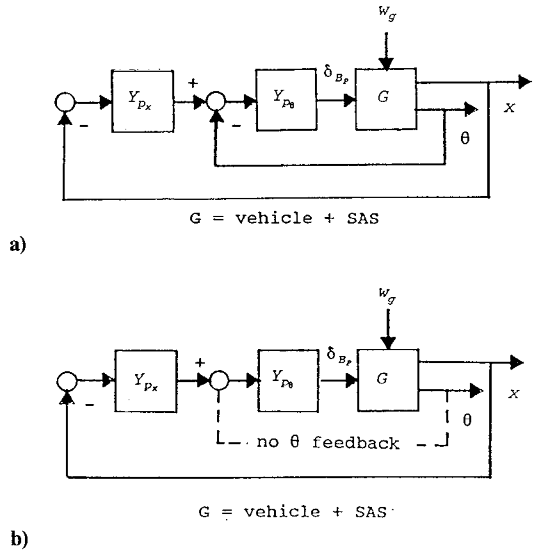

Fig. 3 a) Compensatory and b) pursuit pilot behavior.

selected once the characteristics of the primary-loop dynamics are known in the region of crossover.

As mentioned in the Background section, the structural model has its genesis in the work of Smith.[7] One can show that, when the parameters of the model of Fig. 2 are chosen as outlined above, in accordance with the dictates of the crossover model of the human pilot, the signal u_m will be proportional to primary-loop *output rate* due to control activity. Thus, the model reflects Smith's hypothesis regarding the importance of rate control. As will be seen in what follows, the importance of rate control activity to handling qualities will also be a fundamental aspect of the structural modeling procedure.

Pursuit Behavior

Figure 3a shows the nested or sequential loop structure that would be appropriate for modeling a longitudinal hover task. Note that, in terms of sensing demands on the pilot, two variables are required: pitch attitude θ (radians) and longitudinal displacement x (meters). It has been shown that, in many manual control tasks, the human can adopt what can be termed *pursuit behavior*, represented by Fig. 3b.[25] Such pursuit behavior has been found to be essential for modeling manual control tasks as diverse as aircraft landing[26] and automobile driving.[27]

In terms of human-centered sensing requirements, the advantages of the structure of Fig. 3b, as compared to that of Fig. 3a, are evident. In Fig. 3b, only longitudinal displacement is required, as the attitude loop is no longer closed or, if closed, is only done so infrequently by the human. In addition, it is possible that the crossover frequency of the single-loop system of Fig. 3b can be made considerably larger than that for the outer loop of Fig. 3a, thus ensuring superior tracking performance and disturbance rejection with the latter as compared with the former.

Although presented as two separate control structures, Figs. 3a and 3b may be viewed more accurately as two levels of skill development on the part of the human pilot. The possibility of such control behavior has been discussed in the venerable successive organization of perceptions (SOP) theory.[28] Furthermore, this behavior has recently been experimentally verified in a piloted simulation study involving an altitude regulation task.[29]

The pursuit behavior of Fig. 3b will be utilized in the pilot/vehicle analysis to follow if two criteria can be shown to be met: 1) the same form of pilot compensation Y_{p_n} can be used for pursuit as well as the inner loop compensatory control and 2) adequate phase and gain margins are in evidence with pursuit control (here interpreted as 40 deg of phase margin and 4 dB of gain margin). The criterion requiring no change in pilot compensation for compensatory as compared to pursuit control is part of the underlying manual control theory for pursuit behavior.[25] This criterion lends a certain amount of face validity to ascribing to skill development the transformation of Fig. 3a to Fig. 3b.

Handling-Qualities Sensitivity Function

The use of the structural model of Fig. 2 to analyze vehicle handling qualities was first suggested by Hess and Sunyoto[30] and summarized by Hess.[31] As discussed in these references, the handling-qualities assessment technique originated in the work of Smith.[7] In particular, the numerical pilot opinion rating assigned to a vehicle and task from flight test and simulation data was shown to correlate with the mean-square value of the feedback signal u_m in the structural model of Fig. 2, when the model was used in a pilot/vehicle analysis of the vehicles and tasks in question. This approach follows Smith's lead since, as has been pointed out in the preceding, the signal u_m is proportional to output rate due to control activity, and Smith postulated that rate control was of primary importance in the pilot's perception of a vehicle's handling qualities.

In more recent studies[22,26,27] a HQSF was introduced and utilized. The HQSF, defined as $(u_m/c)(s)$, was found to relate to the handling-qualities *level* assigned to a vehicle and task as follows: If, in the region of the primary-loop crossover frequency, the magnitude of the HQSF exceeded unity, then the vehicle and task would be rated as level 2 or 3 by the pilot. If, on the other hand, the magnitude of the HQSF was below unity in the same frequency region, the vehicle and task would be rated as level 1 by the pilot. The procedure for determining the HQSF so that it is insensitive to control system gains is discussed in Ref. 31.

In applying the HQSF to the analysis of compensatory multi-loop systems (Fig. 3a), only the activity in the primary control loop is considered. When pursuit behavior is hypothesized to exist (when the two aforementioned criteria are met; Fig. 3b), the procedure for determining the HQSF is changed slightly. Details are given in Ref. 26.

V. Hypothesis

The fundamental hypothesis that forms the basis of this study can be stated as follows: Atmospheric turbulence affects the handling qualities associated with a specific vehicle and task by influencing the primary-loop crossover frequencies the pilot must maintain in order to meet the performance requirements that are part of the task definition. Although presented here as a hypothesis, this statement is almost axiomatic when viewed in a control-theoretic context. What transforms the hypothesis from little more than a platitude to part of a useful handling-qualities theory is the fact that the HQSF can be used to reflect the changes in handling qualities that would accompany changes in required crossover frequency due to turbulence.

Viewed in this framework, the fact that turbulence intensity and spectrum can have as significant an effect on vehicle handling qualities as the vehicle dynamics, themselves, is not surprising. In fact, it is almost self-evident.

VI. Example

AH-1G Vehicle Model

The AH-1G rotorcraft alluded to in previous sections will be used in an example pilot/vehicle analysis. The task will be that of maintaining vehicle longitudinal position in turbulence. Only the effects of an upwash field convecting laterally with respect to the nominal vehicle orientation will be considered (i.e., Fig. 1b). The state-space formulation of the vehicle dynamics, as obtained from Ref. 17 and modified with the turbulence gradient aerodynamic model discussed in Sec. III, is presented in Table 1. Note that the complete longitudinal and lateral equations are shown. This is because, in evaluating pertinent longitudinal transfer functions, the effect of lateral control activity will be approximated by assuming tightly constrained lateral feedback loops. The effects of such constraints can be easily handled via coupling numerators,[18] and the calculation of the numerators requires the complete coupled equations of motion.

Four vehicle configurations were utilized in this study. These can be delineated by the characteristics of the vehicle pitch attitude response: 1) no SAS (N-SAS), 2) a command-shaping SAS (CS-SAS) involving no output feedback but providing rate-command-like response to pilot longitudinal cyclic inputs, 3) a *low-gain* attitude command/attitude hold SAS (LG-SAS), and 4) a *high-gain* attitude command/attitude hold SAS (HG-SAS). The SAS configurations are

Table 1 AH-1G aerodynamic model in hover flight condition

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

$$x(t) = \{u, w, q, \theta, v, p, \phi, r, \psi\}^T$$

$$u(t) = \{\delta_{A_p}, \delta_{B_p}, \delta_{C_p}, \delta_{P_p}, w_g, \dot{w}_g\}^T$$

$$A = \begin{bmatrix} -0.0165 & -0.0155 & 0.1114 & -9.805 & -0.0285 & -0.5639 & 0 & -0.0373 & 0 \\ -0.1208 & -0.3726 & -0.0034 & -0.123 & -0.0932 & -0.041 & 0 & 0.6326 & 0 \\ 0.0016 & -0.0109 & -0.2345 & 0 & 0.0022 & 0.2305 & 0 & 0.0175 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.0173 & -0.0051 & -0.4859 & 0 & -0.0552 & -0.3361 & 9.805 & 0.2189 & 0 \\ 0.0280 & -0.0198 & -1.056 & 0 & -0.0285 & -0.7662 & 0 & -0.0403 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ -0.00308 & -0.0154 & -0.1161 & 0 & 0.0518 & -0.3945 & 0 & -0.5366 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} -0.0016 & 0.1491 & -0.0307 & -0.0174 & 0.0155 & 0.0192 \\ -0.0004 & 0.0216 & -1.531 & -0.0037 & 0.3726 & 0.002782 \\ 0.0014 & -0.0575 & 0.003 & 0.0127 & 0.0109 & -0.00742 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0.0971 & -0.0142 & -0.0662 & 0.1540 & 0.0051 & -0.00183 \\ 0.1854 & -0.0270 & -0.0364 & 0.0715 & 0.0198 & -0.00348 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0.0126 & -0.0037 & 0.2282 & -0.3197 & 0.0154 & -0.000477 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Table 2 Definition of vehicle SAS compensators

Command shaping	$G_c(s) = \dfrac{(s+0.3)^3}{s(0.02s+1)^2}$ cm/rad
Low-gain SAS	$G_c(s) = \dfrac{-34.2(s+0.3)^3}{s^2(0.02s+1)^2}$ cm/rad
High-gain SAS	$G_c(s) = \dfrac{-87.11(s+0.3)^3}{s^2(0.02s+1)^2}$ cm/rad

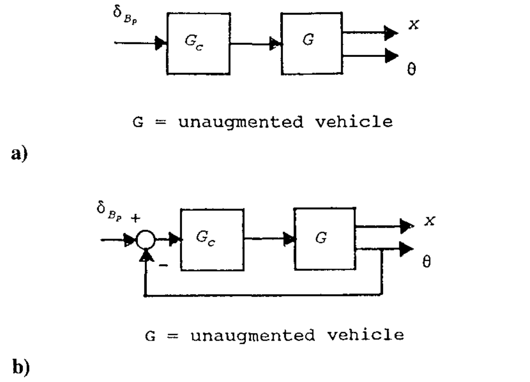

Fig. 4 SAS configurations: a) command shaping (CS-SAS) and b) low and high gain (LG-SAS and HG-SAS).

shown in Fig. 4 and defined in Table 2. Defining bandwidth here as the frequency at which a 3-dB reduction in the zero-frequency amplitude occurs, the bandwidths of the LG-SAS and HG-SAS configurations were 3 and 7 rad/s, respectively. The reader should note that this definition of bandwidth differs from that of Ref. 1.

Pilot Modeling

Space does not permit a detailed discussion of the pilot modeling results. Only an overview will be given here. The selection of crossover frequencies in what follows reflects the author's interpretation of what the hover task would require in terms of pilot/vehicle performance. The pilot modeling procedure for each of the four configurations went as follows:

1) The appropriate coupling numerators were calculated implying tightly constrained lateral control with $\phi \rightarrow \delta_A$ and $\psi \rightarrow \delta_P$, i.e., lateral cyclic tightly constraining roll attitude and tail rotor (pedals) tightly constraining yaw.

2) The appropriate structural pilot model was selected for pitch attitude control with a crossover frequency of 2 rad/s.

3) With the pitch attitude loop closed, an appropriate structural model was selected for vertical translation rate control (with the collective as pilot input) with a crossover frequency of 0.75 rad/s.

4) The possibility of pursuit behavior was investigated using the two criteria previously defined: a) If pursuit behavior was not possible, the compensatory loop structure of Fig. 5a was adopted. The outer loop equalization was chosen as a proportional derivative (PD) type with a crossover frequency of 0.5 rad/s. b) If pursuit control was possible, the pursuit loop structure of Fig. 5b was adopted. The outer loop equalization was again chosen as PD. The crossover frequency was that yielding the minimum stability margins of 40 deg phase margin and 4 dB gain margin.

5) The turbulence transfer functions $(\dot{x}/w_g)(s)$ of Fig. 5 were calculated. In the case of compensatory control, this transfer function had to include the manual attitude and vertical translational rate loop closures. In the case of pursuit control, the transfer function needed only to include the SAS attitude loop closures and the manual vertical translational rate loop closure. In all cases, the lateral variables were tightly constrained but the outer position loop x was *open*.

6) The HQSFs were calculated for each of the manual loops closed.

7) A computer simulation of the pilot/vehicle system was undertaken with the random upwash field described in Eq. (1).

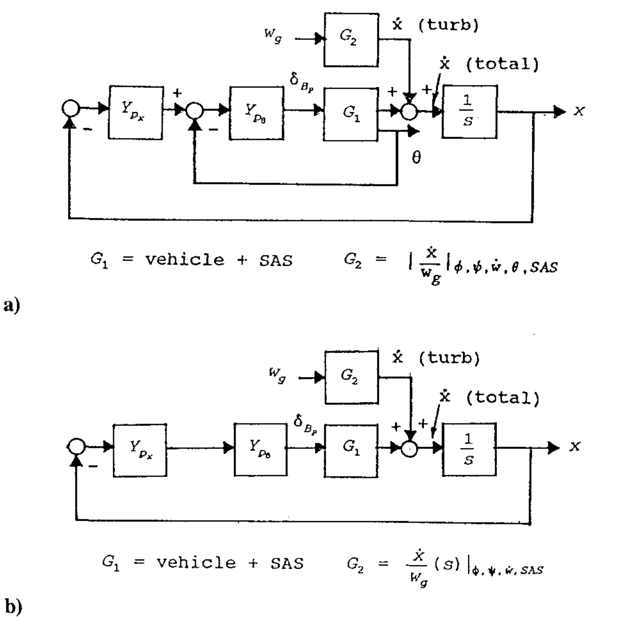

Fig. 5 Pilot/vehicle systems: a) compensatory behavior and b) pursuit behavior.

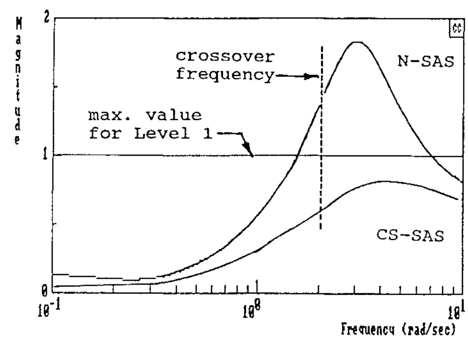

Fig. 6 HQSFs for N-SAS and CS-SAS (compensatory behavior).

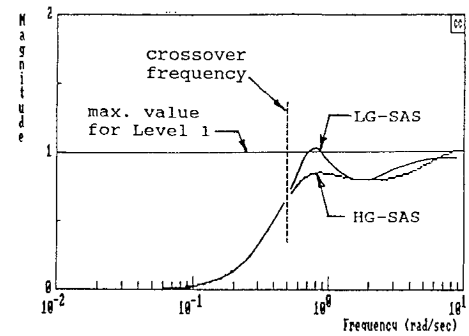

Fig. 7 HQSFs for LG-SAS and HG-SAS (pursuit behavior).

Results

Neither the N-SAS nor CS-SAS configurations allowed pursuit behavior; however, both the LG-SAS and HG-SAS did. The HQSF results are shown in Figs. 6 and 7 for the N-SAS/CS-SAS, and LG-SAS/HG-SAS configurations. The crossover frequencies are denoted on the figures. Note that the CS-SAS, LG-SAS, and HG-SAS would be predicted to yield level 1 handling qualities for the *assumed crossover frequencies*; however the N-SAS vehicle would be predicted as at least level 2.

The first column of Table 3 shows the results of the computer simulation in terms of the rms value of the vehicle center-of-gravity deviation. The superiority of the HG-SAS configuration and the relative parity of the remaining ones is evident in these results.

The definition of the crossover frequencies in the pilot modeling procedure was based upon values that were estimated to be commensurate with acceptable performance in the absence of tur-

Table 3 Results of simulating pilot vehicle system

	Root-mean-square longitudinal deviation,[a] m	
Configuration	(1)	(2)
N-SAS	0.34	0.33
CS-SAS	0.34	0.35
LG-SAS	0.36	0.33
HG-SAS	0.19	——

[a](1) $\sigma_w = 1$ m/s, nominal pilot gain; (2) $\sigma_w = 1.5$ m/s, 1.5× nominal pilot gain.

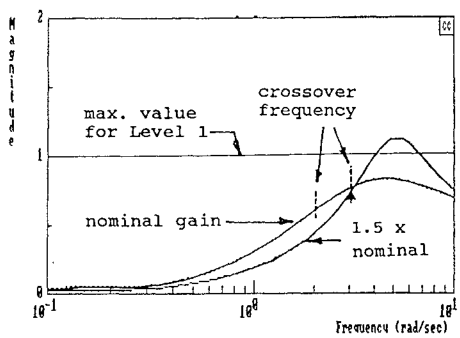

Fig. 8 HQSFs for CS-SAS; nominal pilot gain and 1.5 × nominal pilot gain.

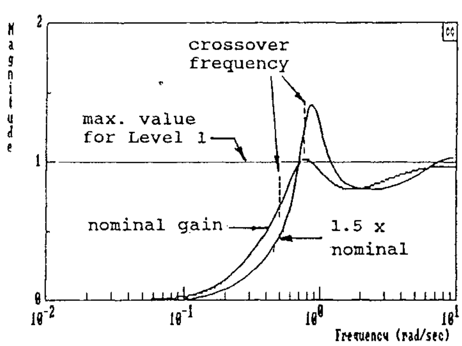

Fig. 9 HQSFs for LG-SAS; nominal pilot gain and 1.5 × nominal pilot gain.

bulence, i.e., those values that would be in evidence if the pilot were simply maneuvering the vehicle near hover in still air. For the purposes of argument, let us suppose that the task definition required a maximum longitudinal excursion of 1.0 m in turbulence. To meet this constraint in an analysis such as this, one might conservatively require a maximum rms excursion of $1.0/3 = 0.33$ m. Within the accuracy of this analysis, the first column of Table 3 indicates that all the configurations meet the performance requirement.

However, if the turbulence intensity were to be increased by 50% to 1.5 m/s, only the HG-SAS would meet the requirement. Since we are dealing with a linear system, one need only multiply the rms values in column (1) of Table 3 by a factor of 1.5 to obtain the rms performance with the increased intensity. Thus, the HG-SAS performance would be 0.29 m and no change in loop crossover frequency would be required of the pilot and hence no change in handling qualities would occur. The same cannot be said of the remaining configurations, all of which would violate the performance constraint with the increased turbulence intensity.

Now, by increasing the gain associated with the pilot models in the remaining configurations by a factor of 1.5 (both inner and outer loops in the compensatory N-SAS and CS-SAS cases), simulation shows that the pilot/vehicle performance meets the 1-m excursion limit. This is indicated in the second column of Table 3. These gain increases are, of course, synonymous with increases in loop crossover frequencies. However, the HQSFs for these increased gain cases predict degraded handling qualities. This is demonstrated in Figs. 8 and 9. Thus, only the HG-SAS is level 1, with the CS-SAS being a "close call." This treatment serves to exemplify the fundamental hypothesis offered in Sec. V that suggests how turbulence can affect handling qualities by requiring increases in primary-loop crossover frequency to meet performance requirements.

VII. Conclusions

Based upon the research summarized herein, the following conclusions can be drawn.

1) A simplified aerodynamic modeling approach allows the effects of turbulence gradients in a convecting frozen field to be included in approximate fashion in rotorcraft equations of motion for the purposes of pilot/vehicle analyses. This approach serves as a *first-order* correction to the approach typically used in analysis of fixed-wing vehicles.

2) The role that turbulence intensity and spectrum have played in experimental handling-qualities investigations for both rotary and fixed-wing vehicles can be understood more clearly by considering their effect on the *closed-loop* pilot/vehicle system and, in particular, on the required crossover frequencies in the primary control loops.

3) Human pilot rate control activity, interpreted here in the proprioceptive feedback loops of the structural pilot model and in the HQSF, appears to be central to many aspects of the manual control problem.

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