Simulation Investigation of the Effects of Helicopter Hovering Dynamics on Pilot Performance

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A fixed-based simulation has been performed to investigate the handling-qualities requirements for the midterm pitch response of a helicopter at hover and in low-speed flight. Pilot rating results from this simulation, using an attitude-tracking task, were compared with those from previous experiments to develop handling-qualities limits on the frequency and damping of the oscillatory mode in the hovering cubic. Pilot performance data obtained during the experiment were used to confirm the pilot-rating results. These data show the pilot performance to closely match that predicted by the theory of piloted control. A means of predicting pilot ratings from the open-loop aircraft dynamics is presented.

Introduction

RECENT advances in rotorcraft technology have greatly expanded the role of the modern helicopter in both peacetime and battlefield environments. It is desirable that the flying qualities of modern helicopters reflect the demands of the particular mission environments. The current helicopter handling-qualities specification, MIL-H-8501A,[1] written in 1952 and largely unchanged since then, does not address the specific handling-qualities issues relevant to today's helicopters. The U.S. Army is currently engaged in revising and updating this document to reflect the advances in rotorcraft technology since 1952 and link it to the design mission environment of a helicopter.

A specific helicopter handling-qualities issue that is dependent on the demands of the mission environment is the response of pitch and roll attitude at hover and low speed. Attitude control at low speed and hover constitutes an important inner feedback loop for piloted control in the performance of a precision task. Other cues used by the pilot, such as position or position rate, usually comprise an outer, lower-frequency loop.

At very low speeds, the pitch-attitude (and, by symmetry, roll attitude) response to longitudinal (and lateral) cyclic for conventional lightly augmented, or unaugmented, helicopters can be approximated[2] by a transfer function of the form

$$\frac{\theta}{\delta_B} = \frac{M_{\delta_B}(s + 1/T_\theta)}{(s + 1/T_{sp})\,(s^2 + 2\zeta_p\omega_p s + \omega_p^2)} \tag{1}$$

The denominator of this transfer function is the classical "hovering cubic."[2] The first-order mode $1/T_{sp}$ is typically at a frequency well above the oscillatory mode described by ζ_p and ω_p. As a result, $1/T_{sp}$ primarily dictates the short-term response (bandwidth[3]) of the helicopter, whereas the oscillatory mode affects the midterm response. The numerator zero $1/T_\theta$ is determined primarily by the stability derivative X_u and is typically less than 0.05 rad/s for helicopters.

The low-speed pitch and roll-handling qualities of a helicopter are determined by the two denominator modes that comprise the hovering cubic. Although good short-term and well-damped midterm responses would be essential for a helicopter operating in a rigorous environment, a lower bandwidth and damping might be adequate for a helicopter operating in a less-demanding environment. In fact, most helicopters in current use (without stability augmentation) have an unstable, albeit low frequency, midterm response, i.e., ζ_p is less than zero and ω_p is typically around 0.5 rad/s.

There is considerable evidence that unstable damping ratios are acceptable to a pilot as long as the natural frequency of the oscillation remains sufficiently low. This evidence comes from existing handling-qualities requirements for helicopters and V/STOL aircraft. Both the fixed-wing V/STOL specification, MIL-F-83300,[4] and the existing MIL-H-8501A[1] permit low-damped and unstable modes. A review of the data base supporting these requirements found them to be largely substantiated by the data. There are, however, some regions with little data (or conflicting results) that warranted further investigation.

A fixed-base simulation was conducted to augment the questionable areas of the helicopter low-speed and hover midterm-attitude-response requirement data base and assist in evaluating the existing requirements in MIL-F-83300 for inclusion in the revised MIL-H-8501. Further insight on pilot control of the inner pitch-attitude loop was gained through measurements of system describing functions obtained during the course of the experiment. Of particular interest were the characteristics adopted by the pilot in controlling low-frequency unstable modes.

Review of the Existing Data Base

A number of simulation and flight experiments have been conducted to investigate the handling qualities of V/STOL's and rotorcraft in hover. Most of these, however, have focused on configurational characteristics peculiar to fixed-wing V/STOL's, such as high gust sensitivity and low vertical-axis response. Hence, for one reason or another, the data from these experiments are not applicable here. The relevant data base consists of results from two experiments, one performed by Seckel et al.[5] on Princeton University's HUP-1 variable-stability helicopter, and the other by McCormick[6] on a moving-base simulator. Variations in pitch-response dynamics were achieved in both experiments through variations in the X_u, M_u, and M_q stability derivatives. In addition, in the McCormick simulation, lateral variations were evaluated separately. The Princeton flight experiment investigated only pitch-response variations. The evaluation tasks in both experiments included precision hover and low-speed circuit-flying (path following) tasks. The Princeton experiment also included a hovering hoop-spearing task. Precise control of pitch and roll attitude is required for the successful execution of

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Presented as Paper 87-2533 at the AIAA Guidance, Navigation, and Control Conference, Monterey, CA, Aug. 17–19, 1987; received Dec. 7, 1987; revision received June 28, 1988. Copyright © 1987 American Institute of Aeronautics and Astronautics, Inc. All rights reserved.

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these tasks. Any configuration with deficient pitch or roll-attitude dynamics would exhibit degraded pilot performance in these tasks and, therefore, degraded pilot opinion.

The results of these two experiments were examined and sorted to exclude configurations with high values of X_u (typical of fixed-wing V/STOL's) and poor lateral dynamics (since we are interested only in a single axis, in this case, the pitch axis). The locations of the oscillatory modes for the relevant data, together with pilot ratings, are shown in Fig. 1. The different symbols in Fig. 1 indicate the flying-qualities levels for the short-term bandwidths of these cases based on the proposed helicopter flying-qualities specification.[3] (Bandwidth[3] is defined as the frequency at which the phase of the open-loop pitch-attitude response to longitudinal stick inputs is -135 deg.) Actual pilot ratings are not given in Ref. 5; the ratings shown in Fig. 1 from this experiment are interpolations from lines of iso-opinion pilot rating (based on the old Cooper pilot-rating scale). The pilot ratings for the Ref. 6 experiment represent averages of individual pilot ratings [based on the Cornell Aeronautical Laboratories (CAL) pilot-rating scale]. Because of the more stringent terminology used on the Cooper scale, pilot ratings from Ref. 5 would probably be about one rating point better if reinterpreted on the Cooper-Harper rating scale (the terminology of the CAL scale is very similar to that of the Cooper-Harper scale).

The MIL-F-83300 boundaries are shown on Fig. 1. The pilot ratings correlate well with the limits for levels 1 and 2. Several pertinent questions about this correlation can be noted:

1) Relatively high-frequency, low-damped modes are allowed by these boundaries. These are in the region of piloted crossover of approximately 1-3 rad/s, a situation that demands a great deal of pilot equalization.[7]

Symbol		ω_{BW} Level (Ref. 3)
Princeton (Ref. 5)	McCormick (Ref. 6)	
△	⊙	1
◊	⊡	2

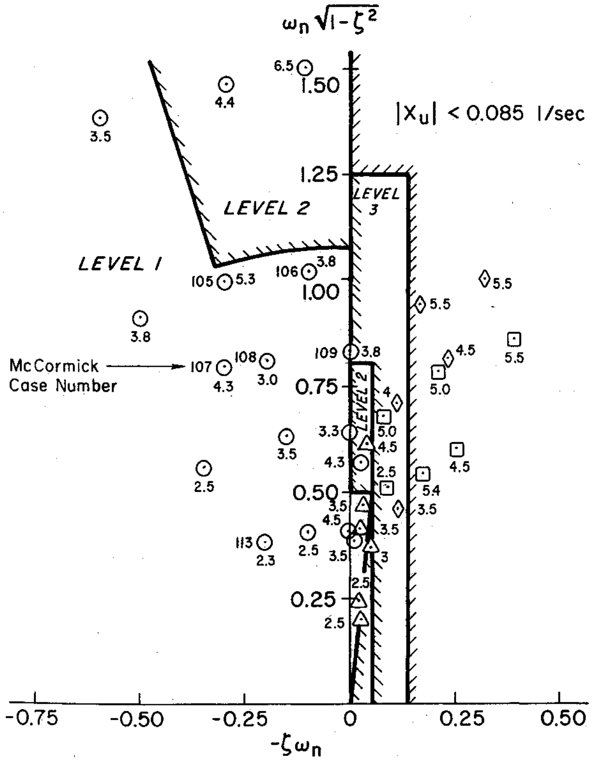


Fig. 1 Location of oscillatory modes for relevant data base—longitudinal variations (lateral fixed) compared with limits of MIL-F-83300 (hover and low speed).

2) There are some discrepancies in the data, e.g., cases 105 and 106, where the configuration with the higher damping (case 105) was given the worse ratings. Cases 107 and 108 show a similar discrepancy.

3) Several configurations with marginal bandwidth lie on the edges of this boundary.

A fixed-base simulation using a pitch-attitude tracking task was constructed to investigate these issues. A pitch-attitude tracking task was chosen because it emphasizes closed-loop pilot control of the inner pitch-attitude loop required to perform any path (outer-loop) maneuver. Hence, it is an effective way to expose deficiencies in the pitch-attitude dynamics.

Experimental Setup and Procedure

The fixed-base simulation was designed to recreate a precision pitch-tracking task. The controlled element Y_c was implemented on an analog computer while the disturbance input generation and data gathering functions were performed by software residing in a digital computer, as illustrated in Fig. 2.

Y_c Mechanization

The controlled element Y_c had the form of the hovering cubic with high-frequency lags approximated by a time delay, i.e.,

$$\frac{\theta}{\delta_B} = \frac{K_\theta(s + 1/T_\theta)}{(s + 1/T_{sp})\,(s^2 + 2\zeta_p\omega_p + \omega_p^2)}\, e^{-\tau_\theta s} \qquad (2)$$

Display

The display was a simulation of an attitude director indicator (ADI) with a pitching horizon and a fixed aircraft indicator, implemented on a CRT scope (Fig. 2). A background grid was available as a pitch-attitude reference.

Stick

The stick was a spring-loaded sidestick with position sensing (described in Ref. 8). It was mounted as a centerstick (see Ref. 8).

Disturbance Function

A quasirandom disturbance input was generated by the controlling software by summing eight sine waves with the frequency and power spectrum shown in Fig. 3. The sine-wave frequencies were selected to span the expected region of crossover for the controlled elements being evaluated. Use of mutually harmonic frequencies was avoided to retain the quasirandom appearance of the disturbance time history. The amplitudes of the component frequencies were shaped to obtain a signal bandwidth of approximately 0.80 rad/s, well below the expected crossover region of 1-3 s, in order to avoid the phenomenon of "crossover regression."[9] The rms magnitude of the input (Fig. 3) was tuned to make the task a realistic one to the pilots.

Conduct of Experiment

Each pilot was allowed to "fly" each configuration and select the control sensitivity before being exposed to the disturbance input. Two runs with the disturbance input, each involving approximately 90 s of closed-loop tracking, were performed for each configuration before assigning a pilot rating and dictating pilot comments. The Cooper-Harper rating scale was used.

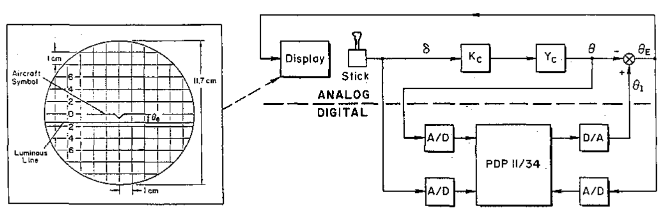


Fig. 2 Simulation architecture.

The configurations were presented in a random sequence and the pilots had no prior knowledge of the configurations. Repeat runs were performed in most cases to allow for the effects of learning.

The task was a pitch-tracking task, where the pilot attempted to null out the pitch-attitude error caused by the disturbance input. Limits for desired performance and adequate performance were set at 1 and 2 deg, respectively.

Pilots

Two pilots were used in the evaluation. Pilot A is an engineering test pilot and an experienced helicopter pilot holding both helicopter and fixed-wing aircraft ratings. Pilot B has had limited exposure to simulations and to helicopter flying but holds a fixed-wing aircraft rating. Both pilots were experienced interpreters of the Cooper-Harper rating scale.

Interpretation of Simulation Results

A pilot performing a visual precision hover task would have to close an inner attitude loop together with an outer position loop (with some position-rate feedback for damping). Only the inner-loop (attitude) dynamics, however, could be evaluated in the fixed-base simulator. Pilot ratings given for this task alone, therefore, would most likely be improved over those given for a task involving outer-loop position control as well, since degraded inner-loop (attitude) dynamics will result in a further degradation in the outer-loop (position) response. The implication is that a marginal level 1 configuration in this simulator would be level 2 or worse in flight.

Configurations

Ten configurations were set up to investigate the regions of interest discussed earlier. These included some repeats of McCormick[6] configurations. Table 1 lists the configurations and their bandwidths.

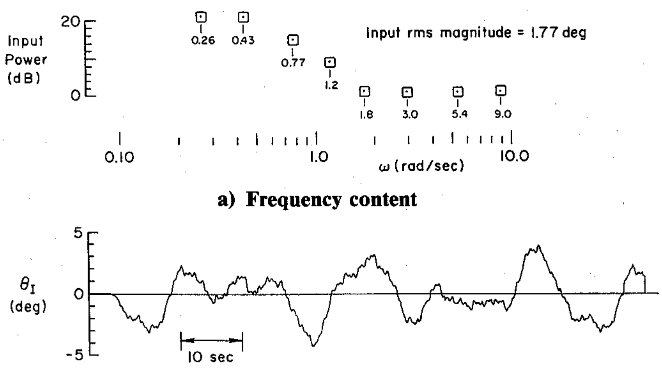
Results

Pilot Opinion

The focus of this experiment was to investigate the appropriateness of the MIL-F-83300 boundaries for adaptation to the revised MIL-H-8501 specification. The pilot-rating results are shown plotted in Fig. 4, repeated from Fig. 1 with the evaluation cases shown as solid symbols. The Princeton[5] data have been omitted from Fig. 4 for clarity.

The primary tie-in case with the data from Ref. 6 was configuration 8, equivalent to case 113 in Ref. 6. This configuration was rated level 1 by both pilots, and this result agreed with that from Ref. 6. In addition to having level 1 phugoid characteristics, this configuration also had a pitch bandwidth of 3.9 rad/s, which is well within the proposed level 1 bandwidth requirement.[3]

Configuration 1, situated in the level 1 region of MIL-F-83300, was given level 2 ratings by both pilots, together with



a) Frequency content

b) Time history

Fig. 3 Disturbance input.

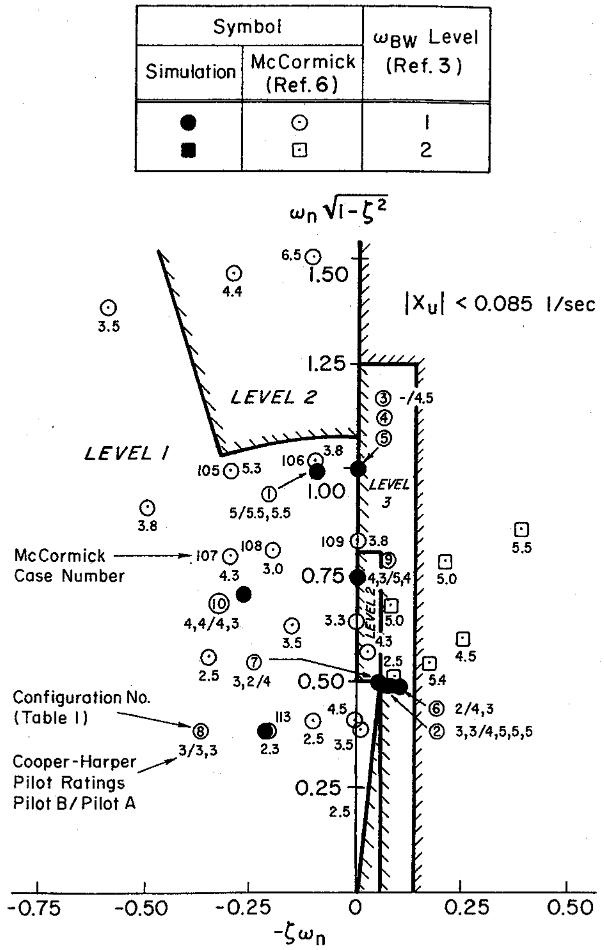


Fig. 4 Configurations evaluated on fixed-base simulation.

Table 1 List of configurations

Configuration	θ/δ_B	Bandwidth, rad/s
1	$\frac{(0.05)e^{-0.08s}}{(1.0)\ [0.1;\ 1.0]}$	1.4
2	$\frac{(0.05)e^{-0.08s}}{(1.2)\ [-0.17;\ 0.5]}$	0
3	$\frac{(0.05)e^{-0.125s}}{(3.6)\ [0;\ 1.0]}$	2.0
4	$\frac{(0.05)e^{-0.125s}}{(1.0)\ [0,\ 1.0]}$	1.0
5	$\frac{e^{-0.125s}}{[0,\ 1.0]}$	1.0
6	$\frac{(0.05)e^{-0.125s}}{(4.7)\ [-0.20;\ 0.5]}$	2.0
7	$\frac{(0.05)e^{-0.08s}}{(1.85)\ [-0.125;\ 0.5]}$	1.0
8	$\frac{(0.05)e^{-0.08s}}{(6)\ [0.47;\ 0.43]}$	3.9
9	$\frac{(0.05)e^{-0.125s}}{(3.8)\ [0;\ 0.75]}$	2.0
10	$\frac{(0.05)e^{-0.125s}}{(2.0)\ [0.35;\ 0.75]}$	2.0

Note: $(a) \equiv (s+a)$; $[\zeta;\omega_n] \equiv [s^2 + 2\zeta\omega_n s + \omega_n^2]$

comments such as "tendency to PIO" and "sluggish-unpredictable." This result is not surprising given the low bandwidth and the relatively high frequency of the phugoid mode (Table 1)—factors that cause the available phase margin in the region of piloted crossover to be marginal. The ratings for a similar configuration in Ref. 6 (case 106, with an average rating of 3.8 in Figs. 1 and 4), however, are somewhat better: 3, 4, and 4.5. An additional case evaluated in Ref. 6 (case 105, with the same frequency as case 106 but with higher damping) received solidly level 2 ratings in that simulation (ratings of 5, 5, 6 for an average of 5.3). Hence, this case was rated level 2 despite its relatively higher-damped phugoid mode and level 1 bandwidth. This discrepancy in the results of Ref. 6 and the strong opinions of the pilots about configuration 1 gave some merit to the investigation of a more restrictive level 1 boundary in the positively damped region of Fig. 4.

Configurations 9 and 10, with level 1 pitch bandwidths of 2.0 rad/s, were developed specifically to test a more restricted boundary. These were given marginally level 1 and level 2 ratings by the pilots. The ratings for configuration 10 are consistent between pilots as well as with Ref. 6 data as indicated by the point in Fig. 4 with a slightly higher frequency and an average pilot rating of 4.3 (case 107 in Ref. 6). Comments for configuration 9 were similar to those given for configuration 1, but the ratings show that desired performance could be obtained in this case.

The ratings and comments for configurations 9 and 10 indicated that a lowering of the allowable frequency of the phugoid mode might be appropriate. Although acknowledging the differences in the simulation task and setup between Ref. 6 and this experiment (moving vs fixed base, precision hover vs pitch tracking), it was the opinion of both subject pilots that a helicopter with pitch characteristics similar to those exhibited by configuration 1 would definitely be outside the level 1 boundary.

Configurations 3, 4, and 5 were not expected to yield results considerably different from those for configuration 1 and, hence, these configurations were not investigated in any detail. It is interesting to note, however, that pilot A ascribed a better rating to configuration 3 than for configuration 1. This is probably due to the higher bandwidth of configuration 3 (Table 1).

The remaining three configurations (2, 6, and 7) differed in bandwidth but had very similar (unstable) phugoid modes on the level 1 boundary. Figure 5 shows the trend of pilot rating with bandwidth for these configurations, and indicates that they are marginally level 1, if $\omega_{BW} = 1$ rad/s (the proposed level 1 bandwidth for the revised specification). The low bandwidth of configuration 7 was noted by both pilots in their comments on the lack of crispness and unpredictability of the response. The ratings for these three configurations show bandwidth to be the deciding factor. The phugoid mode, although unstable, seemed to have been of sufficiently low frequency to have been stabilized, with little compensation by the pilots.

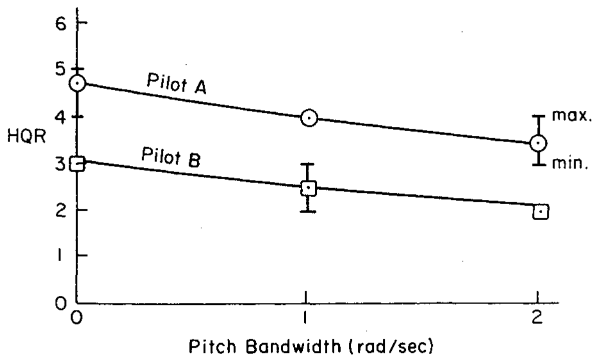


Fig. 5 Effect of bandwidth on average pilot rating for configurations with marginal phugoid characteristics (configurations 2, 6, and 7).

The results of this experiment are conservative in that the pilot ratings are equal to or worse than the ratings for similar configurations in Ref. 6, even though only a single-axis task was simulated. On that basis, it is reasonable to combine the ratings with those obtained in Ref. 6, as shown in Fig. 4. These combined ratings support a need for a more stringent level 1 boundary, and *less* stringent level 2 boundary, such as those sketched in Fig. 6. The level 1 boundary is more consistent with the proposed bandwidth requirement for $\omega_{BW} > 1$ rad/s (i.e., the old MIL-H-8501A boundary allowed essentially zero damping at $\omega_n = 1$ rad/s). It also recognizes the difficulty the pilot will encounter when trying to equalize a controlled element with a low-damped second-order mode close to the region of crossover,[7] discussed in the next section.

Pilot Performance

Factors Governing Piloted Loop Closure

References 7 and 10 provide a detailed overview of the factors governing the pilot loop closures necessary to perform a precision hover. A brief summary of the factors governing the inner pitch-attitude loop simulated in this experiment is appropriate at this point as a precursor to the discussion of the quantitative measures of pilot performance from the experimental data. The pitch attitude to longitudinal cyclic transfer function of the OH-6A,[11] with an added time delay of 0.08 s to represent system lags, will be used as an example. Configuration 7 in the piloted simulation approximated this transfer function (Table 1).

For the OH-6A at hover, the hovering cubic is[11]

$$\frac{\theta}{\delta_B} = \frac{0.75\,(s + 0.011)\,e^{-0.08s}}{(s + 1.86)[s^2 + 2(-0.112)(0.476)s + (0.476)^2]} \tag{3}$$

A systems survey of the inner pitch-attitude closure using a pure-gain pilot with a representative transport delay[9] of 0.25 s

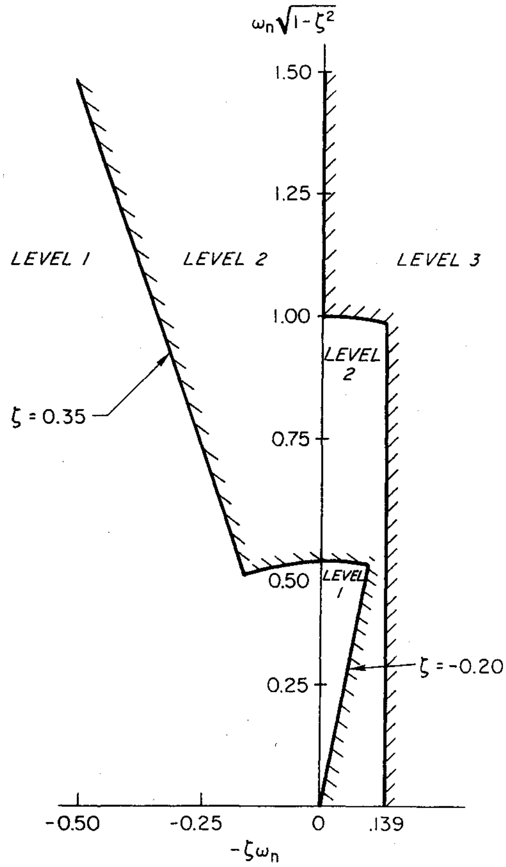


Fig. 6 Revised proposed limits on pitch (roll) oscillations (hover and low speed).

is shown in Fig. 7. The main factor governing the closure is the need to drive the first-order aperiodic mode $1/T_{sp}$ as close as possible to the numerator zero $1/T_\theta$ while keeping the damping of the closed-loop phugoid mode at a manageable level. The closed-loop roots for a nominal pilot gain ($K_p = 5$) are shown (primed) in Fig. 7b. The closed-loop Bode plot for this nominal-gain closure is shown in Fig. 7c.

Equalization of $1/T_\theta$ with the closed-loop $1/T'_{sp}$ is essential for minimizing the closed-loop low-frequency droop exhibited by the amplitude ratio (Fig. 7c). Such equalization is necessary to ensure good closed-loop tracking performance (minimizing tracking error). A pure-gain pilot attempting this equalization through an increase in gain is faced with vanishing stability margins due to the migration of the phugoid mode into the right half plane (Fig. 7b).

The human operator is capable of improving stability margins to provide some "room for maneuver" through the adoption of lead as dictated by the human-pilot crossover model.[9] The effect of adding a pilot lead at 2 rad/s is also shown in Figs. 7a and 7b. The closed-loop roots for the same nominal gain as for the pure-gain pilot (Fig. 7b) show the substantial improvement in the damping of the closed-loop phugoid root ω'_p. The improved phase margin also can be seen in the open-loop Bode plot (Fig. 7a). The addition of pilot lead, however, incurs a cost in terms of pilot-rating decrement and an increase in the equivalent transport delay.[9]

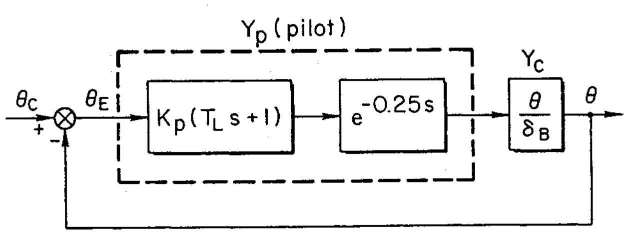
As discussed in Ref. 7, the proximity of the phugoid mode to the expected crossover region of 1–3 rad/s is also important to pilot performance and opinion. The closer the frequency of the phugoid mode is to the crossover region, the more difficult it is for the pilot to equalize the response dynamics to the preferred K/s dynamics[9] in that crossover region.

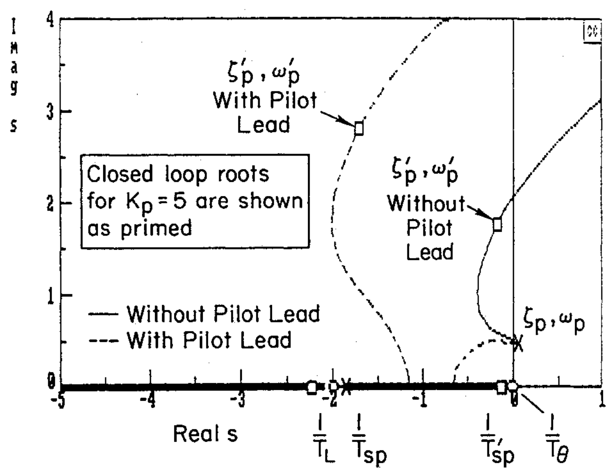
As stated previously, a pilot would have to close an outer-position loop in addition to the inner pitch-attitude loop in order to successfully perform a hover or stationkeeping task. The expected crossover region for the outer loop as dictated by its dynamics is in the region of 0.2 rad/s or less. The inner- and outer-loop crossover regions are therefore well separated in frequency and there is little or no interaction between them. The pilot can therefore optimize the inner-loop closure without jeopardizing outer-loop performance.

Pilot Model Analysis

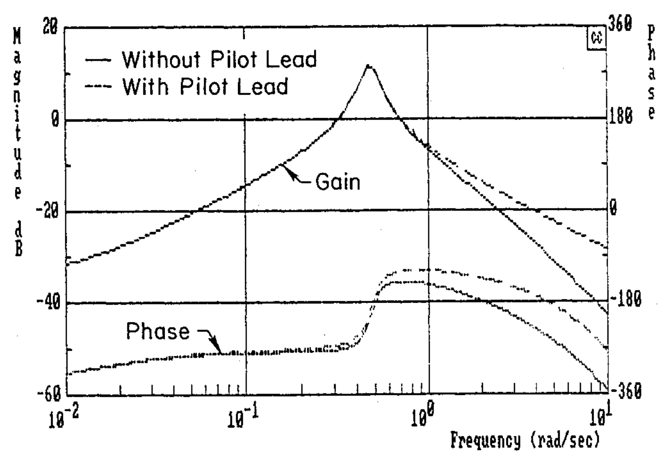
Various performance measures such as rms tracking error and stick activity, together with open- and closed-loop describing functions, were obtained for each run through the experimental software. Typical open- and closed-loop describing-function plots are shown in Fig. 8.

Examination of the open-loop (Y_pY_c) data showed the average crossover to be at 2.57 rad/s (standard deviation of 0.33 rad/s)—within the expected crossover range for this controlled element. Figure 9 shows the variation of pilot rating with the open-loop phugoid frequency for all configurations with level 1 bandwidths ($\omega_{BW} \geq 1$ rad/s). As theorized previously, there is a definite degradation in pilot rating as the frequency of this mode approaches the crossover-frequency range. A similar compilation of flight and simulator data[5,6] can be found in Ref. 7.

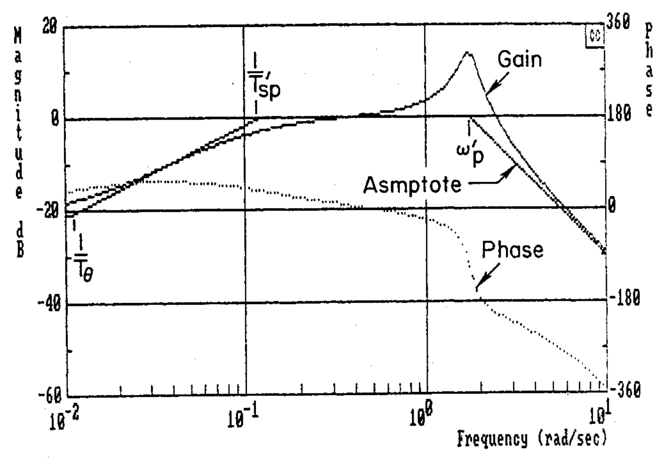




b) Root locus of piloted loop closure (with and without pilot lead)

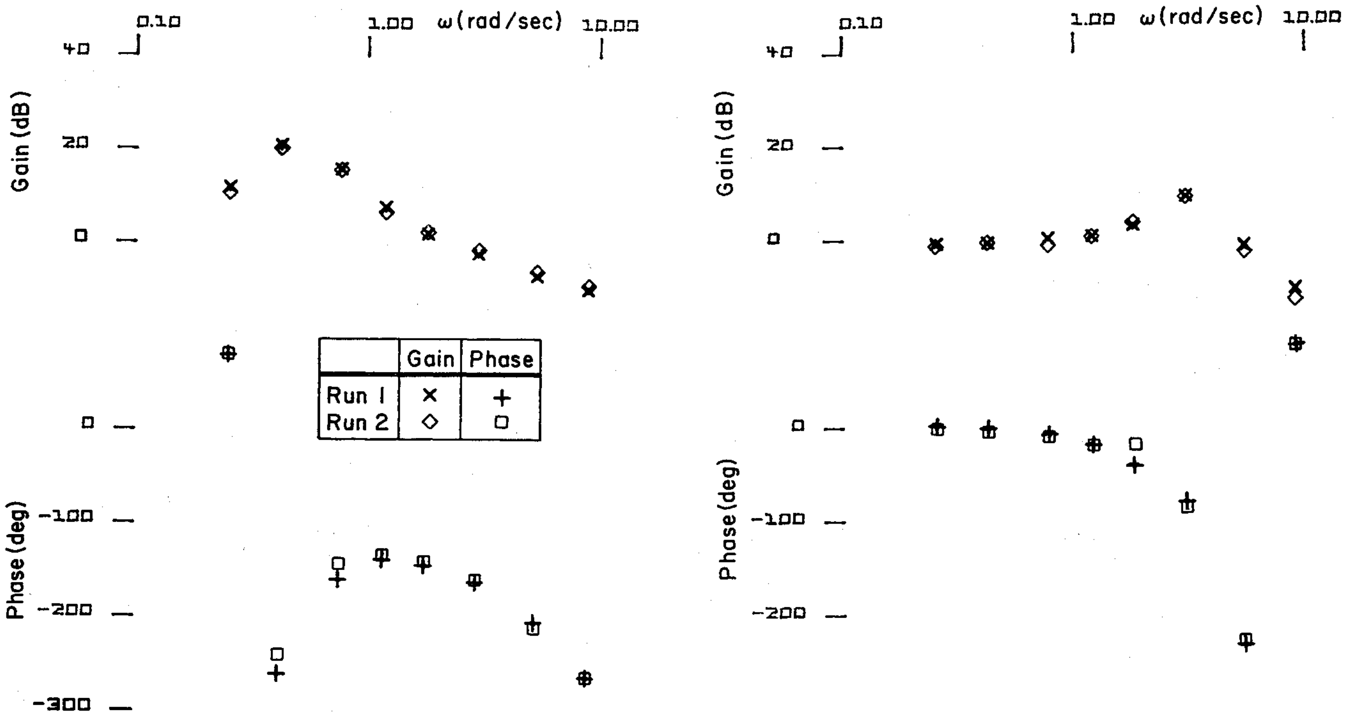


a) Open-loop bode plot (with and without pilot lead)



c) Closed-loop bode plot (pure gain pilot)

Fig. 7 Systems survey of assumed pilot-loop closure of OH-6A pitch attitude at hover.



a) Open-loop (Y_pY_c) describing function

b) Closed-loop $[Y_pY_c/(1 + Y_pY_c)]$ describing function

Fig. 8 Typical describing-function data plots (configuration 6, pilot B).

Using the open-loop (Y_pY_c) describing-function data, pilot models were extracted for all of the configurations and data runs. The assumed pilot model was the simplified precision model[9] shown below:

$$Y_p = K_p \frac{(s + 1/T_{\text{lead}})}{(s + 1/T_{\text{lag}})} e^{-\tau_p s} \tag{4}$$

where the high-frequency pilot neuromuscular dynamics are included in the time-delay term τ_p.

Model fits to the (Y_pY_c) data were performed using a nonlinear weighted-least-squares optimization method.[12] These matched parameters were then cross-checked against the closed-loop $Y_pY_c/(1 + Y_pY_c)$ data. The mismatch parameter[12] in the majority of the cases was within the satisfactory range, and any case with an unsatisfactory mismatch value was not included in the analysis.

In all cases, the extracted pilot model reduced to a pure gain or first-order lead, with a time delay. The average calculated time delay for all runs and both pilots was 0.266 with a standard deviation of 0.037 s. It is interesting to note that this average value is very close to the pilot time delay of 0.269 s that would be expected based on the crossover model,[9] assuming a pure-gain pilot and an input bandwidth of 0.8 rad/s.

Representative open-loop Bode plots and loop-closure root loci for two configurations are shown in Fig. 10. The loop closure closely represents the theory presented earlier.

The effect of total pilot phase lead or lag at a crossover frequency of 2.50 rad/s (approximate average crossover) on pilot opinion is shown in Fig. 11. As expected, there is a degradation in pilot opinion with increasing pilot lead.

In order to get an a priori estimate of pilot opinion for a certain airframe, it would be of great advantage to be able to estimate the degree of pilot compensation (lead or lag) needed for good closed-loop preformance and stability, given the open-loop airframe dynamics Y_c. One possible method of accomplishing this is to compare the performance of a hypothetical pure-gain pilot to that of the pilots in the experiment,

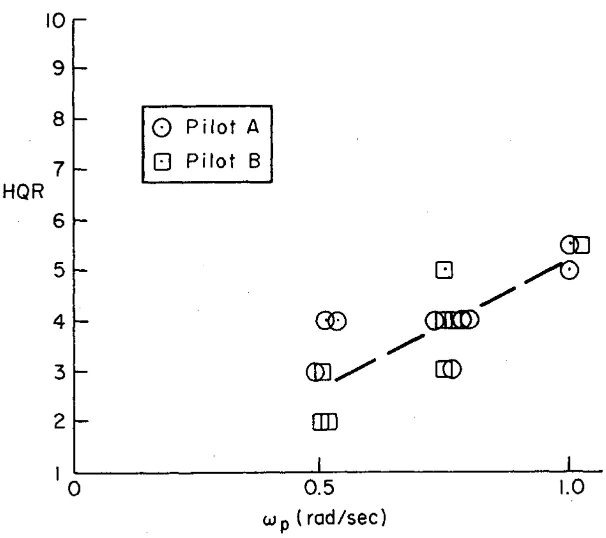
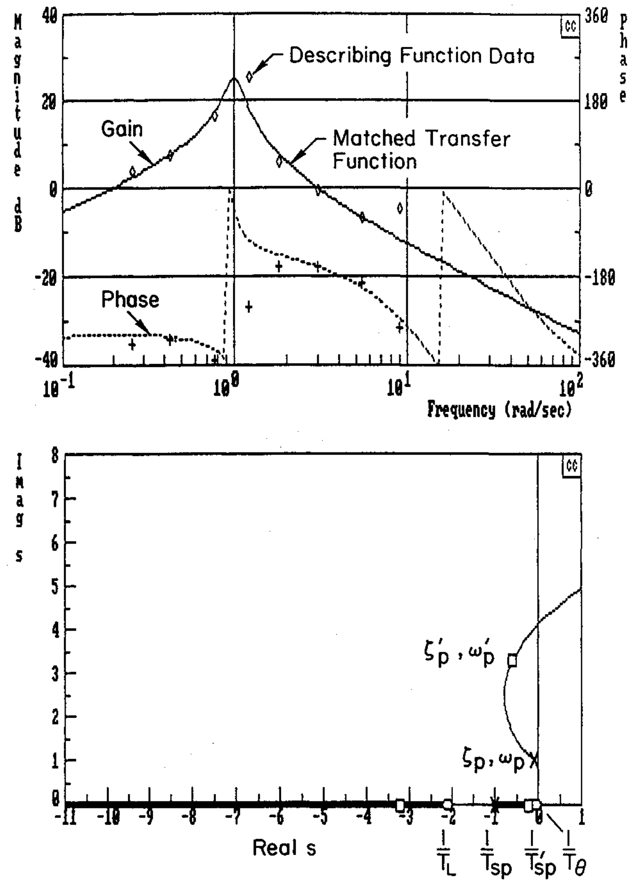


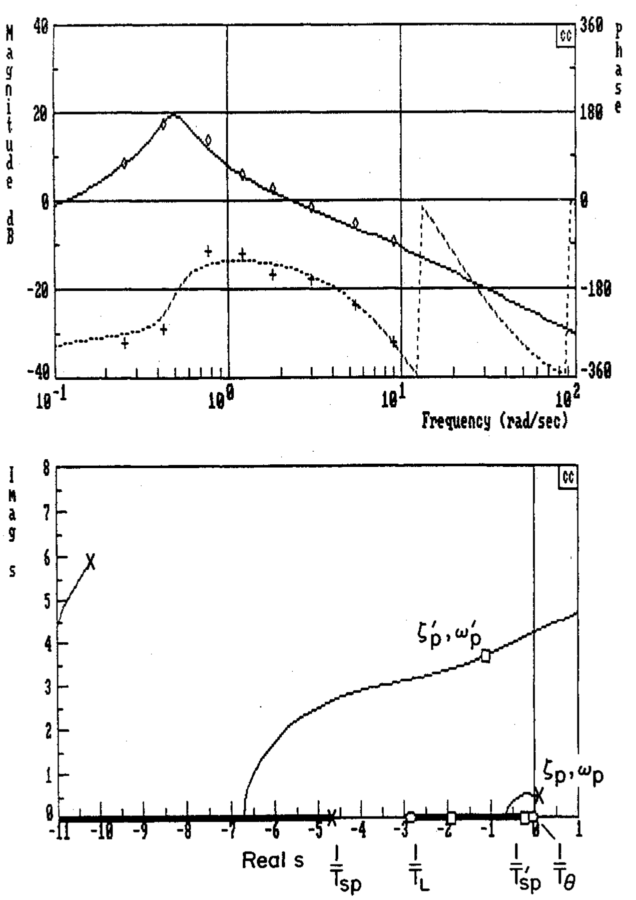
Fig. 9 Effect of phugoid frequency on pilot opinion.

a method similar to that pursued for fixed-wing airplanes by Neal and Smith.[13]

The closed-loop performance parameters chosen for this analysis were the low-frequency magnitude ratio droop as described by the ratio of $1/T_\theta$ to $1/T'_{sp}$ (Fig. 7c) and the closed-loop phugoid damping ratio ζ'_p identified previously (see Fig. 7b). As before, a pure-gain pilot with a 0.25-s time delay was assumed and the loop closed with the gain (K_p in Fig. 7) required to give an open-loop crossover frequency of 2.5 rad/s. The correlation between the performance parameters for the pure-gain pilot, and the actual compensation required at 2.5 rad/s (as obtained from the experiment), is shown in Fig. 12. The resulting correlation coefficient r^2 of 0.719 is within the 99% confidence bound. The relationship in Fig. 12 is therefore a possible means of indirectly estimating pilot opinion for these types of controlled elements.



a) Configuration 1 (pilot A)



b) Configuration 6 (pilot A)

Fig. 10 Representative open-loop Bode and root loci from simulation.

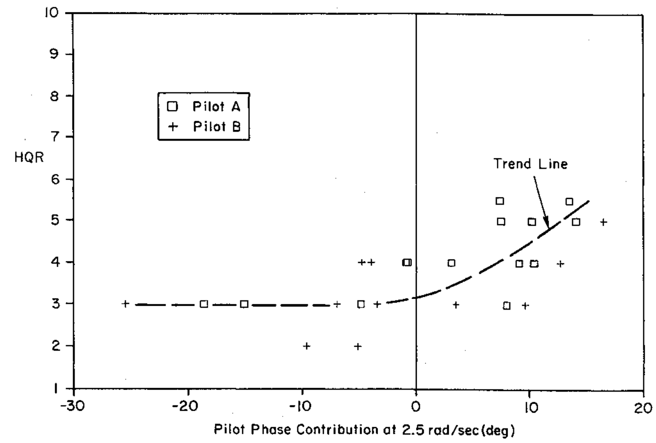


Fig. 11 Effect of pilot equalization on pilot rating.

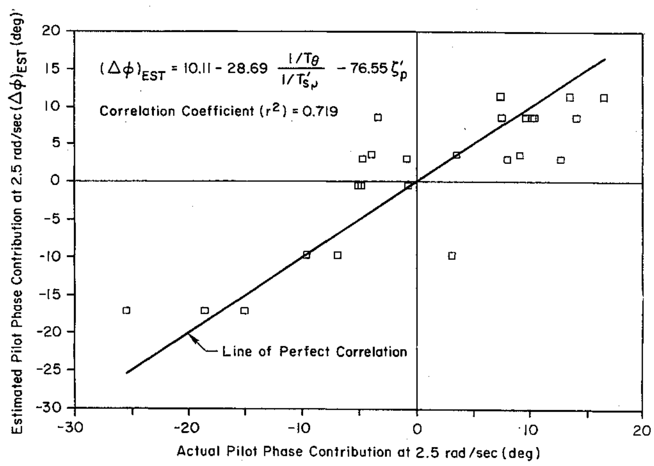


Fig. 12 Actual vs estimated pilot equalization.

Conclusions

The objective of the simulation reported in this paper was to investigate and gain insight into the effects of helicopter low-speed midterm attitude response dynamics on pilot opinion and performance.

The pilot-rating results for this simulation, when combined with the existing data base, support the need for a more stringent level 1 handling-qualities requirement on the midterm response, specifically excluding low-damped oscillatory modes close to the region of piloted crossover. Pilot ratings and comments confirmed that such modes were unsatisfactory.

A pilot-model analysis of the describing-function data obtained during the experiment showed the pilot as a pure gain, or first-order lead controller, with some time delay. The analysis also showed that the pilot performance closely resembled that predicted by the crossover model. A comparison of the actual pilot performance with that of a hypothetical, pure-gain pilot, provided a feasible means of predicting pilot opinion given the open-loop aircraft dynamics.

Acknowledgment

The research reported in this paper was performed under Contract NAS2-11304 from the Army Aeroflightdynamics Directorate, ARTA, Moffett Field, CA. Mr. Chris L. Blanken was the contract monitor.

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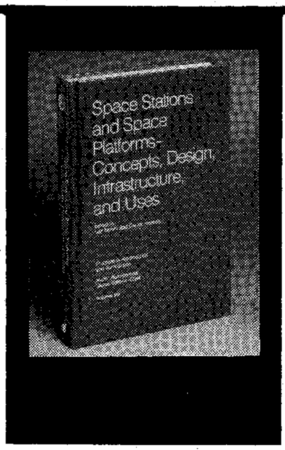

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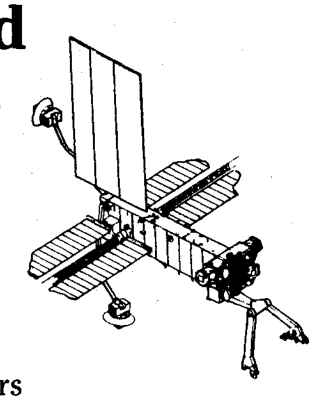

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