Flight Investigation of Helicopter Low-Speed Response Requirements

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A flight experiment has been conducted using a variable-stability airborne simulator to define the dynamic response requirements for operations at hover and low speeds. Fourteen attitude command/attitude hold, rate, and rate command/attitude hold configurations were evaluated by six pilots using both conventional controls and a four-axis integrated sidestick over a low-speed course consisting of precision hover, landing, sidestep, and dash/quickstop tasks. The results indicate that, with conventional controls, all three response-types were acceptable as long as their response bandwidths were sufficiently high, and higher bandwidths were required in roll than in pitch. With the four-axis sidestick, there was a preference for the rate systems. The range of acceptable bandwidths was lower, and the spread in pilot ratings smaller, than were found in a similar ground-based simulation.

Introduction

THE military specification for helicopter handling qualities, MIL-H-8501A,[1] is over 25 years old. In this span of time, the steady evolution in rotorcraft technology, encompassing the fields of avionics, flight control systems, rotor systems, cockpit controllers, and so forth, and the corresponding increase in demands from the rotorcraft, have resulted in aircraft that are far more sophisticated than MIL-H-8501A can address. Some of the specific shortcomings have been described in detail by Key[2,3] and Clark and Goldstein.[4]

In response to the inadequacies of MIL-H-8501A, the U.S. Army and Navy have undertaken an extensive effort to produce an upgraded document that will apply to today's (and tomorrow's) rotorcraft. A proposed specification and background document directed toward advanced rotorcraft has been produced,[5,6] and work is currently in progress to expand this proposed specification to encompass all rotorcraft classes and missions, i.e., a revised version of MIL-H-8501A.

Throughout the specification development and revision process, it has been very clear that there is a lack of substantiating data for defining new requirements for rotorcraft. As a result, a series of simulations and flight tests has been conducted with the goal of augmenting the data base. Flight experiments have been performed, and continue to be performed, in the United States, Great Britain, West Germany, and Canada. The National Aeronautical Establishment (NAE) of Canada has been most actively supporting this process[7] using a variable-stability airborne simulator (a modified Bell 205A-1 helicopter).

This paper reports on the results of an experiment directed at defining the pitch and roll response requirements for low-speed maneuvering. Three fundamental questions were addressed: 1) What is the appropriate short-term response characteristic (response-type) for a particular task? 2) What are the minimum acceptable response dynamics? 3) What are the differences for a conventional cockpit control arrangement vs an integrated four-axis sidestick? While several experiments have been conducted to evaluate these questions, most have used ground-based simulators.[8-12] A piloted simulation (documented in Ref. 13) conducted on NASA Ames Research Center's vertical motion simulator in 1984 investigated the first two questions by varying response bandwidths for a variety of cases with rate command/attitude hold, rate command/attitude retention, attitude command/attitude hold, and translational rate command response-types. One of the goals of the flight tests reported in this paper was to reproduce a selected portion of the evaluations from the Ref. 13 simulation.

Experiment

There were four major variables in the experiment: 1) task; 2) cockpit controller configuration; 3) pitch and roll response characteristics (response-type); and 4) bandwidths of the pitch and roll responses.

Task Variations

The handling qualities tasks are illustrated in Fig. 1. The course shown in Fig. 1 was flown a minimum of three times for each configuration. As a result, the pilot performed nine precision hover tasks, nine landings, and three sidesteps and dash/quickstops, for a flying time of between 20 and 30 min

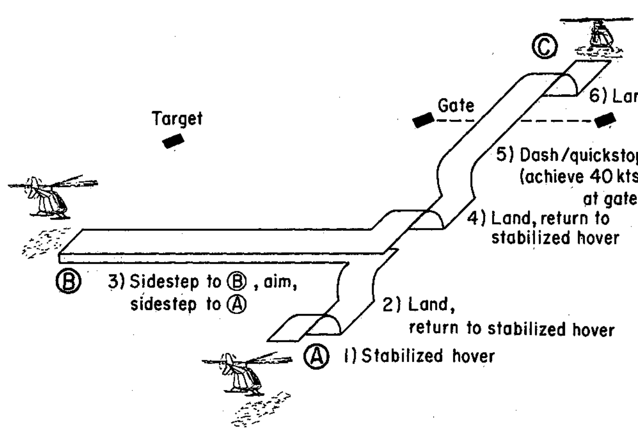

Fig. 1 Task scenario.

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Table 1 Dynamics of cases evaluated

Case	Response type	Pitch characteristics: Bandwidth ω_{BW_θ}, rad/s	$\tau_{p\theta}$, s	q_{pk}/q_{ss} $[\theta_{pk}/\theta_{ss}]$	Roll characteristics: Bandwidth ω_{BW_ϕ}, rad/s	$\tau_{p\phi}$, s	p_{pk}/p_{ss} $[\phi_{pk}/\phi_{ss}]$
0	ACAH	1.75	0.21	[1.1]	1.6	0.26	[1.0]
1	ACAH	2.7	0.22	[1.0]	2.8	0.18	[1.0]
2	ACAH	2.7	0.20	[1.0]	3.1	0.12	[1.1]
3	ACAH	2.4	0.28	[1.0]	2.8	0.29	[1.1]
4	RCAH	0.75	0.17	1.0	1.2	0.33	1.2
5	RCAH	1.9	0.19	1.0	1.5	0.14	1.0
6	RCAH	2.0	0.25	1.0	2.0	0.23	1.0
7	RCAH	2.8	0.15	1.8	2.3	0.14	2.0
8	RCAH	0.85	0.05	1.7	1.0	0.22	1.8
9	RCAH	1.6	0.30	1.1	1.85	0.16	1.0
10	Rate	1.5	0.15	1.2	3.0	0.12	1.0
11	Rate	1.8	0.09	1.1	3.4	0.12	1.0
12	Rate	2.2	0.17	1.1	1.9	0.13	1.0
13	Rate	1.9	0.21	1.0	3.0	0.11	1.3

Notes: Bandwidth parameters are defined in Fig. 2. Overshoot ratio, x_{pk}/x_{ss} (where $x = q, \theta, p, \phi$), is defined as the ratio of first peak to steady-state x response for a step control input.

for each evaluation. For desired performance, precision hover required a stabilized hover over a designated spot with deviations of no more than 1 ft in any direction, and landing required touchdown with no more than a 2 ft deviation. Adequate performance was defined as twice these values. For the sidestep and dash/quickstop, the pilots were required to perform the tasks as aggressively as possible, ending each maneuver with a return to a stabilized hover at a specified point.

Handling qualities ratings (using the Cooper-Harper rating scale) and comments were obtained for four tasks: hover, landing, sidestep, and quickstop.

Cockpit Controllers

Two cockpit controller arrangements were used for the evaluations. The conventional control arrangement included a centerstick cyclic, left-hand collective, and pedals. Cyclic force/deflection gradients were approximately 2 lb/in. and breakout forces were 0.5 lb in both pitch and roll. The sidestick controller was an integrated four-axis force-sensing stick (Measurement Systems, Inc. small-displacement controller) with limited motion and self-centering in all axes. All controller force and deflection characteristics were optimized during presimulation development.

Linear response shaping (in terms of attitude or rate commanded per unit control input) was used in all axes. The pilots were allowed to optimize control/response sensitivities for each configuration before starting a formal evaluation. Sufficient control power was available in pitch and roll to perform all of the tasks without reaching control limits, and there were no comments from the pilots to indicate that the control/response characteristics were adversely influencing the evaluations.

Configurations

Fourteen pitch and roll configurations were evaluated, covering a wide range of response-type and response bandwidth. The primary response-types were attitude command/attitude hold (ACAH), rate command/attitude hold (RCAH), and pure rate (without any hold capability). All of the systems employed full-time pitch and roll rate feedbacks. Attitude feedback was added to achieve the ACAH response-types, and an integral-plus-proportional feedforward element was included for the RCAH systems.

The yaw control system was a rate command/heading hold response type. For the conventional-controller evaluations, with a displacement-type collective, heave control was the basic Bell 205A. Since large sustained inputs are not possible with a force-sensing sidestick, it was necessary to add a parallel integrator to the output of the sidestick collective to provide long-term trim. The integral/proportional ratio was not optimized, so the additional integration resulted in an undesirable acceleration response. The aircraft was judged to be level 1 in the directional axis and in the vertical axis with the conventional collective, but handling qualities were degraded somewhat in the vertical axis with the sidestick; this is discussed further in the Results section.

Response Characteristics

The short-term dynamics of the 14 cases were developed on-line, varying feedback gains via potentiometers in the cockpit until the desired pitch and roll responses were attained. The intent was to produce a range of responses that varied time delay, overshoot ratio, and bandwidth, corresponding to the range tested in the earlier simulation.[13] Dynamics of the configurations were identified using computer-generated "frequency sweeps."[14,15] The time histories were fast-Fourier transformed to produce frequency responses (Bode plots). The short-term response characteristics (bandwidths) of the configurations were then determined from these frequency responses.

Table 1 summarizes the characteristics of the 14 cases. The bandwidth parameters, ω_{BW} and τ_p, are defined in Fig. 2. The feedback gains were adjusted to make the response bandwidths as symmetric as possible in the pitch and roll axes, and, as Fig. 3a indicates, this was achieved for most of the cases. The phase delay parameter, representative of high-frequency effects (Fig. 2), does not show quite as much symmetry (Fig. 3b).

Pilots

Six evaluation pilots participated in the study. Four pilots flew both the conventional-control and sidestick evaluations. Almost 150 runs were performed, covering all 14 cases, 4 tasks, and 2 controller arrangements, resulting in approximately 600 pilot ratings.

Results for Conventional Controls

Figure 4 summarizes the handling qualities ratings (HQR) from the conventional-controller evaluations as a function of pitch and roll bandwidth. Each symbol represents between three and six evaluations of each variation case. It is important to note that, since Fig. 4 shows only bandwidth, it does not account for the effects that variations in phase delay or overshoot ratio (Table 1) may also have had on HQR. Cases

Phase Delay:

$$\tau_p = \frac{\Delta\Phi 2\omega_{180}}{57.3(2\omega_{180})}$$

Rate Response-Types:

ω_{BW} is lesser of $\omega_{BW_{gain}}$ and $\omega_{BW_{phase}}$

Attitude Command/Attitude Hold Response-Types (ACAH):

$\omega_{BW} \equiv \omega_{BW_{phase}}$

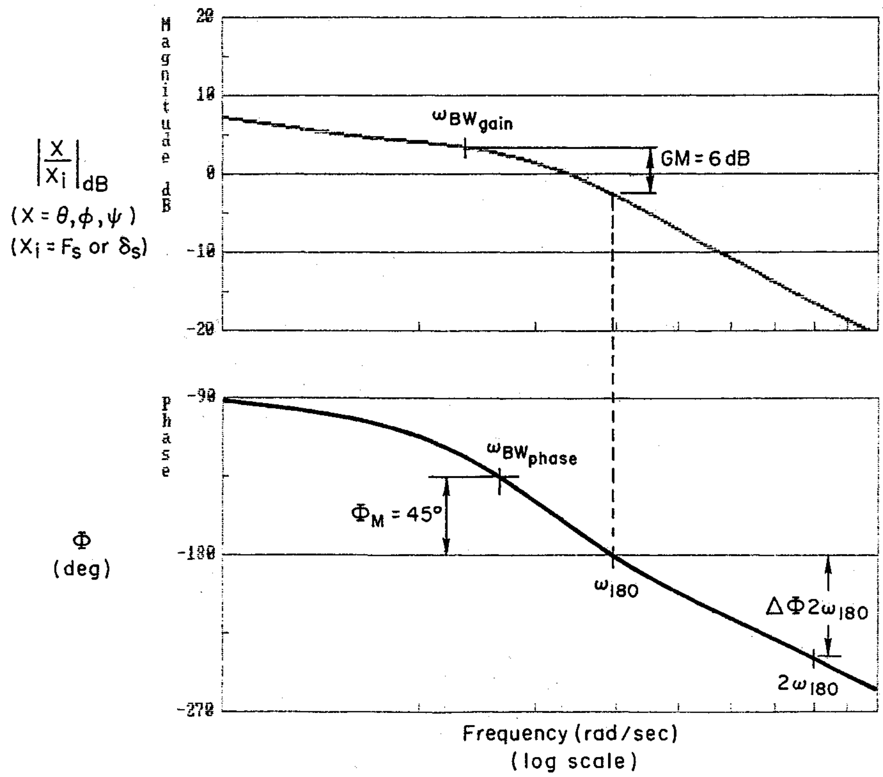
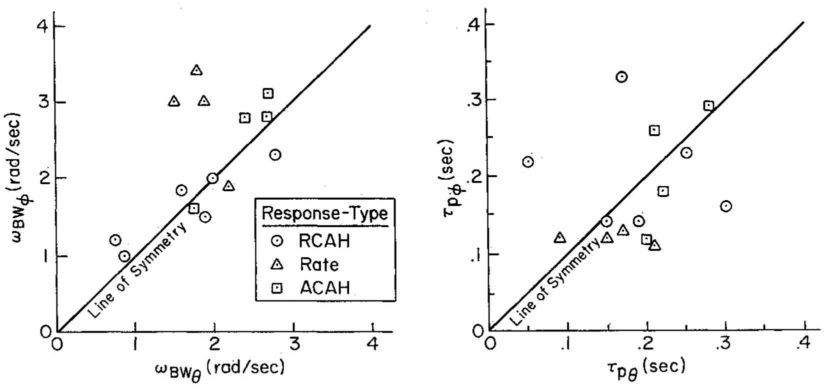


Fig. 2 Definitions of bandwidth and phase delay.[5]



a) Bandwidth frequency b) Phase delay

Fig. 3 Comparison of pitch and roll bandwidth parameters for cases of Table 1.

6 and 7 were devised to investigate the importance of overshoot ratio; these cases are labeled in Fig. 4 and will be discussed subsequently.

The following discussions will focus on the most significant results from the experiment, using the conventional-controller data. The effects on handling qualities of pitch and roll response-type, task, bandwidth, and overshoot ratio are discussed. Phase delay τ_p was not directly varied in the experiment, so there is no information available for setting upper limits on phase delay alone. Throughout this discussion, comparisons are made with the results of the V/STOL shipboard landing simulation,[13] which involved similar response characteristics and similar tasks (though in a different environment).

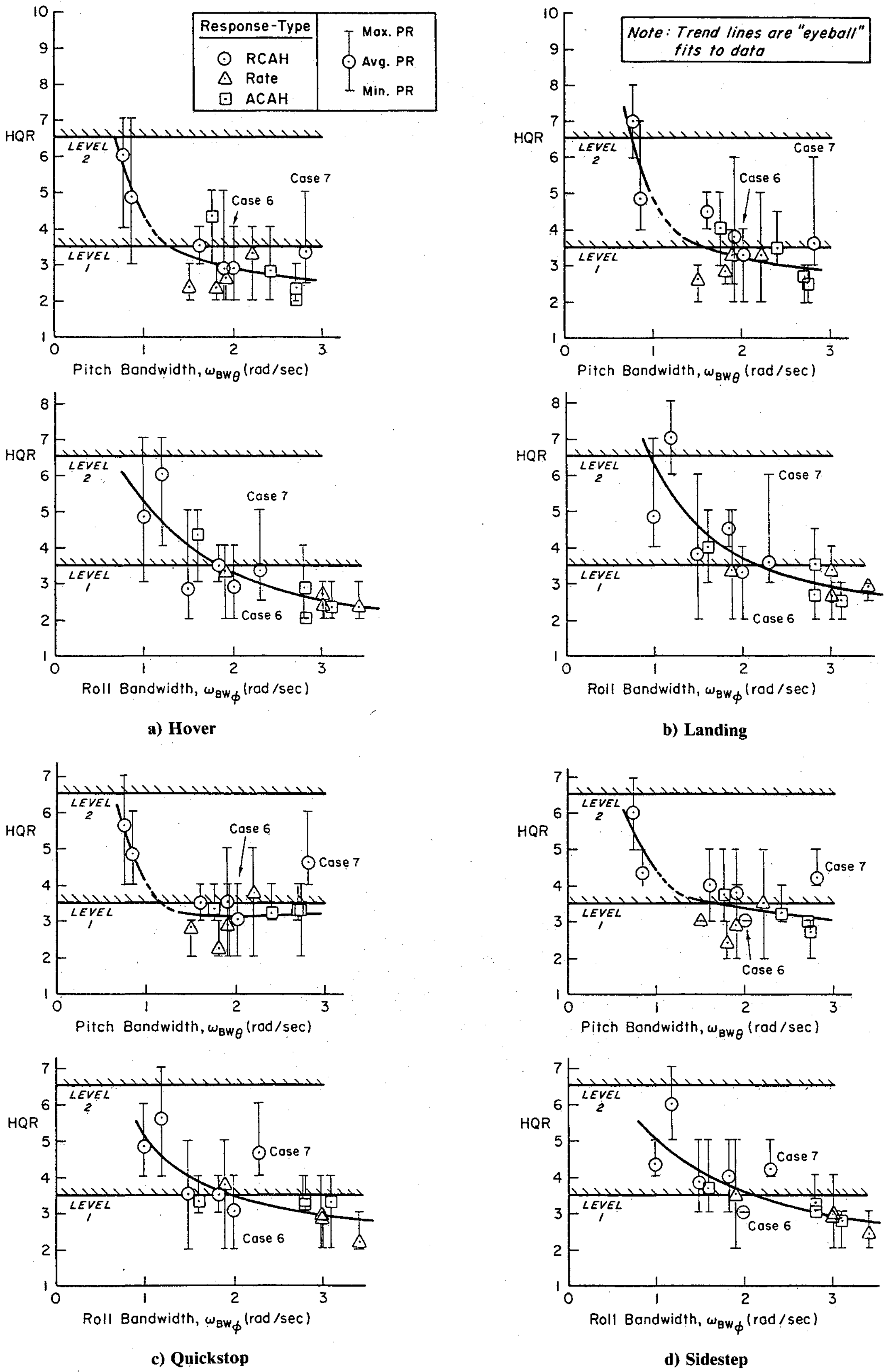
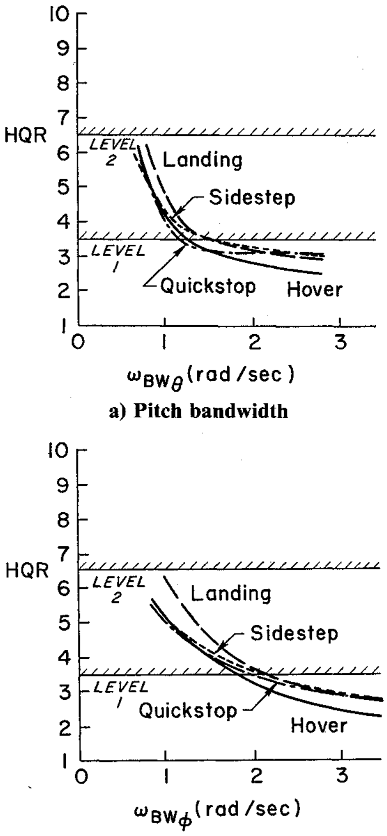


Fig. 4 Handling qualities ratings vs pitch and roll bandwidth (conventional controllers).

Effect of Pitch and Roll Response-Type

It was expected, based on studies of response requirements for low-speed maneuvering[16] and on simulation results,[9,13] that there would be some pilot rating differences between the three response types. For example, attitude command has been considered[9,16] to be the most desirable for precision low-speed operations, where a stable vehicle is essential, and hence would be expected to be favored for the hover and landing tasks. Rate command is considered to be preferred for rapid maneuvering, such as the sidestep and dash/quickstop. Because most of the evaluations were made in a light-to-moderate level of turbulence, attitude hold would be desirable as a measure of gust rejection.

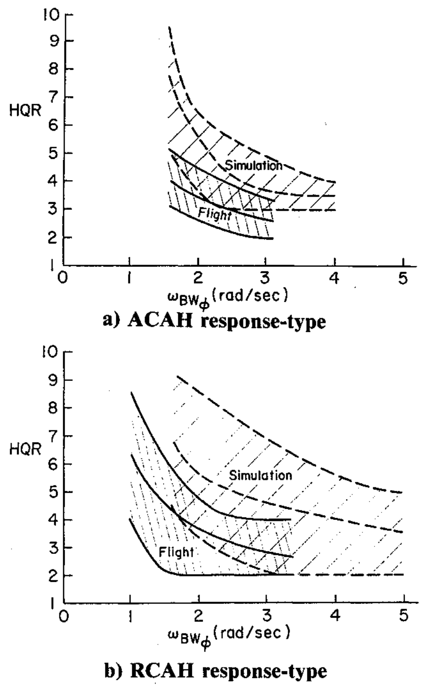
The data of Fig. 4 do not show any significant differences in pilot ratings among the three response-types evaluated. The range of tested bandwidths is greater for the RCAH systems



a) Pitch bandwidth

b) Roll bandwidth

Fig. 5 Summary of average rating curves from Fig. 4.



a) ACAH response-type

b) RCAH response-type

Fig. 6 Comparison of handling qualities ratings ranges from simulation[13] and flight (Fig. 4b) for landing.

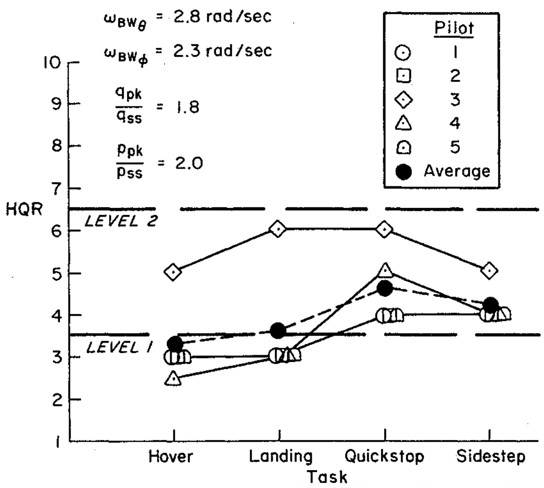


Fig. 7 Handling qualities ratings for high-overshoot configuration (case 7); conventional controllers.

than for either the pure rate or the ACAH systems; within the range flown, however, it appears that the pilots were, for the most part, indifferent to the specifics of the short- or long-term response. Other studies have shown that ACAH is preferred over RCAH for operations in low visibility,[17] and that RCAH is preferred over ACAH for air combat,[11] but the current results indicate that for low-speed, noncombat operations in good visibility, such differences do not exist.

Effect of Task

Figure 5 summarizes the average-pilot-rating curves from Fig. 4. Task effects on handling qualities can be inferred from the differences in these curves. As Fig. 5 shows, the precision hover task was the easiest overall (i.e., the average ratings are better), while the landing task was the most difficult. The fact that landing was more difficult than precision hover is consistent with simulation results;[13] it is interesting, however, that the quickstop and sidestep tasks were also somewhat easier than the landing task. In general, there are only slight differences in the average-rating curves for all four of the tasks.

Effect of Pitch and Roll Bandwidth

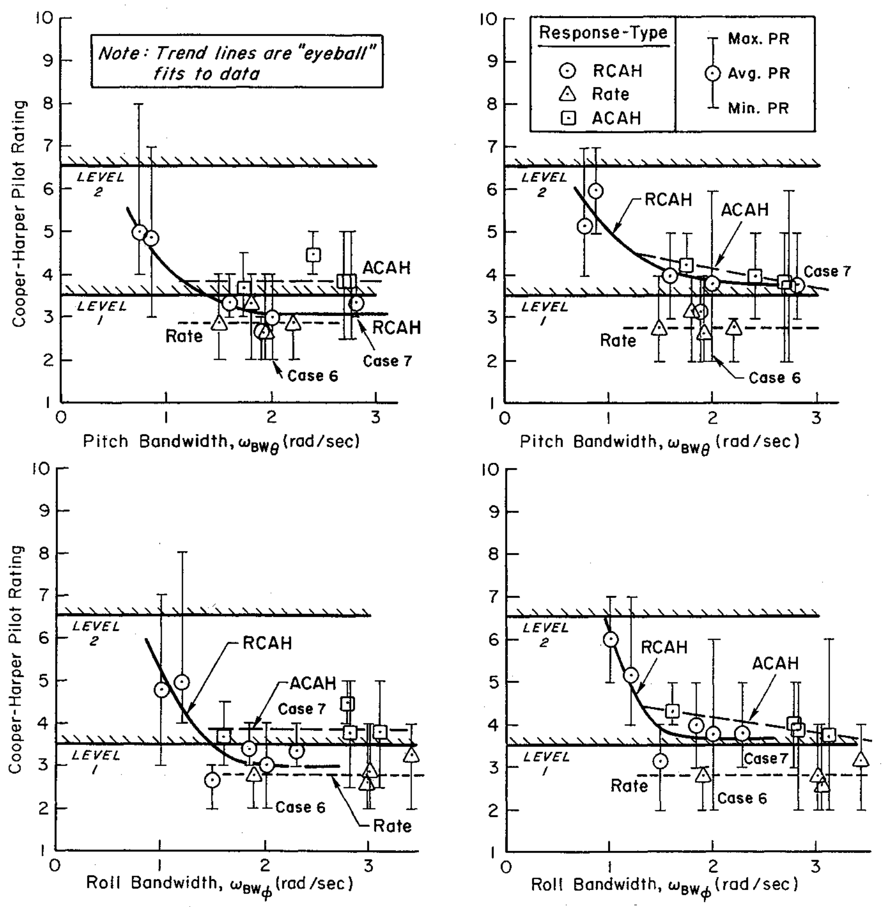
In the V/STOL simulation[13] it was found that a bandwidth of at least 3 rad/s was necessary to obtain consistent level 1 pilot ratings (handling qualities ratings between 1 and 3-1/2), while configurations with bandwidths below 2 rad/s were level 3 (HQRs greater than 6-1/2). As discussed in Ref. 13, the degraded visual and motion environment of the simulator, compared with flight, probably influenced the results, resulting in more stringent bandwidth requirements than in the real world. For the flight experiment, the pitch and roll bandwidths were devised to cover a range between 1 and 3 rad/s, encompassing the handling qualities level range based on the simulation results.

As Fig. 5 shows, bandwidths less than 3 rad/s were acceptable in flight. In addition, there is a difference in the variation of HQR with bandwidth for pitch vs roll; Fig. 5 suggests that the pilots were more sensitive to roll bandwidth. Based on Fig. 5, a pitch bandwidth as low as about 1 rad/s is acceptable (level 1), while the level 1 limit in roll is about 2 rad/s. It is important to remember, however, that the same sets of pilot ratings were used for both the pitch and roll bandwidth plots of Fig. 4. Thus, it is not possible to determine from these data what the independent limits on bandwidth are for the pitch and roll axes. To do this, it would be necessary to fix the bandwidth in one axis at a good value and vary the bandwidth in the other axis.

Figure 6 shows a comparison of the range of HQR's for the landing task from simulation[13] and from flight (Fig. 4b). As this figure indicates, a much wider variation in pilot ratings was obtained in the simulator, especially for the RCAH systems (Fig. 6b). None of the RCAH systems evaluated in the simulator received consistent level 1 ratings. It is important to note that two of the pilots who participated in the simulation also served as evaluation pilots on the flight experiment.

Effect of Overshoot Ratio

A characteristic inherent to many rate systems is some initial overshoot in the rate response to a step control input.



a) Quickstop b) Sidestep

Fig. 8 Handling qualities ratings vs pitch and roll bandwidth for four-axis sidestick (quickstop and sidestep only; ratings for hover and landing are similar to centerstick ratings of Fig. 4).

(For attitude systems, overshoot ratio is directly related to system damping, and hence limits on damping ratio effectively limit overshoot ratio as well.) There is little information available, however, for setting limits on allowable levels of this overshoot. Most of the configurations evaluated in the flight experiment were designed to have little or no overshoot, as Table 1 shows. Two of the cases (cases 7 and 8) were included specifically to investigate whether high levels of pitch and roll rate overshoot resulted in handling qualities problems. The pilot ratings for case 7 are particularly insightful; case 8 also has a low bandwidth in both pitch and roll, so it is difficult to isolate the effect of overshoot from that of bandwidth on pilot opinion.

Figure 7 shows the individual HQR's from the five pilots for case 7 as a function of task. This case (also identified on Fig. 4) was acceptable to four of the five pilots for the hover and landing tasks. For the quickstop and sidestep, all five pilots considered it to be level 2. The ratings from pilot 3 were consistently higher, and his comments reflect an objection to the abruptness of the response, even at low control sensitivities. Other pilots also noted the abrupt response, but they considered it more an annoyance than a handling qualities deficiency.

As a point of contrast, case 6, with a lower bandwidth (2.0 rad/s in pitch and roll, Table 1) but no overshoot, is also identified on Fig. 4. Unfortunately, pilot 3 did not fly this case, so it is difficult to make a direct comparison with case 7; it is clear from Fig. 4, however, that this configuration was considered to be better than case 7. Especially significant are the ratings for the sidestep (Fig. 4d), where all four pilots gave case 6 ratings of 3, compared with ratings of 4 for case 7 (Fig. 7).

The data of Fig. 7 support placing some limit on the allowable overshoot ratio for pitch and roll rate response-types, though it is not possible to determine what that limit might be, except that it should be somewhat less than 1.8.

Results for Integrated Four-Axis Sidestick

The four-axis small-displacement sidestick controller used in the experiments used twist for yaw control and vertical force commands for heave control. As discussed in the Experiment section, the response dynamics in the heave axis were acceleration-like and hence were inherently deficient for the four-axis sidestick. Because of the inadequacies in the vertical axis, and because the intent of the experiment was to study pitch and roll response requirements, the pilots were instructed to ignore any shortcomings in height control in their ratings. Informal discussions with the pilots indicated that the height-control portion of the landing task was a Cooper-Harper handling qualities rating of 4–5 with this controller.

Results for the precision hover and landing tasks, with the four-axis sidestick, were very similar to those for the conventional controls (Figs. 4a and 4b) and are not shown here. The most significant differences were found for the dash/quickstop and lateral sidestep tasks. A summary of handling qualities ratings as a function of pitch and roll bandwidths for these tasks is shown in Fig. 8. The overall range of ratings, and the variations in average rating with bandwidth, are similar to those of Figs. 4c and 4d.

There is a significant difference in HQR for the three response types in Fig. 8. The rate configurations were preferred, while the ACAH configurations were rated the poorest. All four of the ACAH configurations received level 2 average ratings. In the conventional-control evaluations, Figs. 4c and 4d, only one was considered to be level 2.

For a multi-axis task like the dash/quickstop, inputs are required into every axis essentially simultaneously: cyclic to initiate the translation (pitch nose-down), up collective to

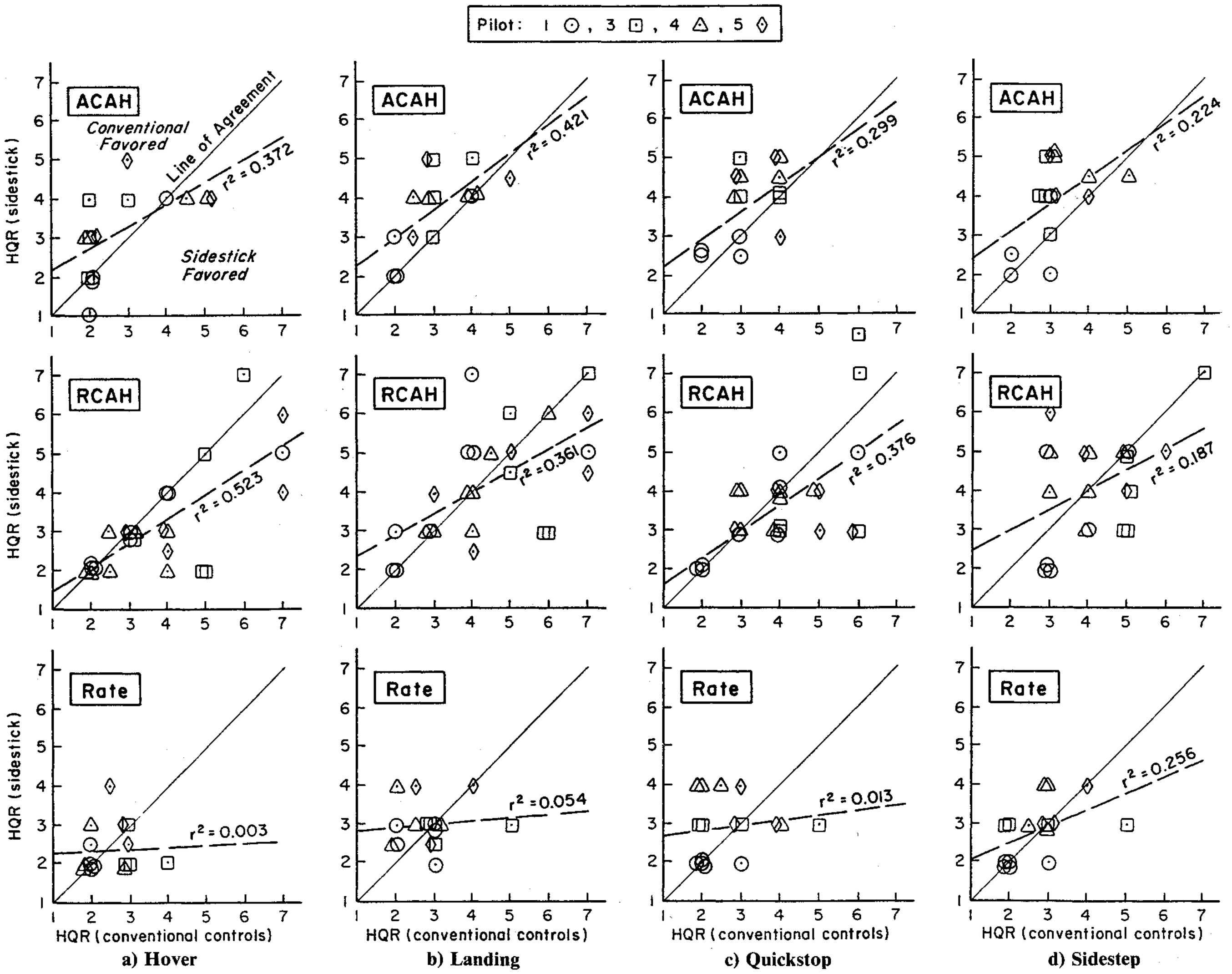


Fig. 9 Crossplot of handling qualities rating from conventional-control and four-axis sidestick evaluation. Dashed lines are linear regression fits to data; r^2 is the coefficient of determination.

arrest the resulting sink rate, and roll and yaw corrections for coupling, turbulence, etc. With an attitude command system, the maneuver requires a step cyclic input, i.e., the pilot must hold a forward force throughout the forward translation. At the same time, the collective, roll and yaw inputs must be made. With ACAH this can result in very uncomfortable and difficult control forces and hand/arm positions. Hence, ACAH is a degradation in response-type for a four-axis force-sensing sidestick.

The effect of overshoot ratio discussed in the previous section was not found for the sidestick evaluations. Case 7, with overshoot ratios of 1.8 in pitch and 2.0 in roll, received pilot ratings that were very close to those for case 6, which had no overshoot. These cases are also noted in Fig. 8.

Comparison of Pilot Ratings for Conventional and Sidestick Controls

Four of the six test pilots flew both the conventional and sidestick control arrangements. The pilot ratings from these evaluations are analyzed in this section for a one-to-one comparison of the effects of control arrangement on pilot opinion.

Figure 9 shows a crossplot of handling qualities ratings from the conventional and sidestick evaluations for each case in Table 1. In a few instances, a repeat run was flown for one of the control configurations; these are included as separate data points in Fig. 9. Pilot ratings that lie on the left of the diagonal line are those cases where the centerstick ratings were better than the sidestick ratings (i.e., centerstick was favored), and points to the right are cases where the sidestick was favored. Points along the diagonal line of agreement represent those cases where the ratings were equal for both controller types.

A least-squares linear regression fit[18] was performed for all of the data of Fig. 9 to the standard form

$$y = mx + b$$

where $y = \text{HQR}$ for sidestick evaluation, $x = \text{HQR}$ for conventional-control evaluation, $m = \text{slope}$, and $b = \text{y-axis}$ intercept.

The dashed lines in Fig. 9 show the linear regression fits for each set of data. The coefficient of determination r^2 is noted next to each line. This coefficient, in combination with the number of samples, indicates the confidence with which it may be assumed that the two ratings are correlated (using the statistical T or Student's distribution[18]). For almost every condition, the pilot ratings are correlated to greater than a 95% level of confidence (i.e., the likelihood of obtaining r^2 as large as those noted purely by chance is less than 5 in 100). The only exceptions are the ratings for the rate response types for the hover, landing, and quickstop tasks (where the linear regression fit is almost horizontal, and these ratings are uncorrelated at greater than a 95% level of confidence).

Great care must be exercised in interpreting the results of Fig. 9. As mentioned previously, the pilots were told to ignore any deficiencies in the vertical response for the sidestick in their evaluations, so the sidestick ratings in Fig. 9 may be considered to be for a three-axis, rather than a four-axis task. Some general trends can be observed, however. For example, for the ACAH response-types, the linear regression lines are shifted to the left of the centerline for all tasks, supporting the observations made in the previous section that the conventional controls were preferred for ACAH.

The slopes of the regression lines in Fig. 9 indicate that the pilots were less sensitive to changes in dynamics with the sidestick than with conventional controls. This can be seen by observing that the slopes of the lines are all less than unity; a unity slope would reflect an equal incremental degradation in handling qualities for both controller arrangements, while a slope greater than unity would suggest that the pilots were more sensitive to changes in handling qualities with the sidestick than with the conventional controls.

Finally, the pilot rating comparisons in Fig. 9 also suggest that the pilots preferred the conventional controls when handling qualities were good, but may have favored the sidestick as handling qualities degraded. If the conventional controls were uniformly better, most of the ratings would lie above the centerline, as they do for the ACAH response types. For the RCAH and rate response types, this is not true; for RCAH, especially, the majority of the ratings were better for the sidestick than for the conventional controls.

While the question of vertical-control influences on HQR diminishes the impact of these observations somewhat, an analysis of the results of a simulation investigation of separated sidestick controls vs an integrated four-axis sidestick[9] shows very similar trends.

Conclusions

For operations with a conventional arrangement (centerstick cyclic, left-hand collective, and pedals), the flight experiments conducted with a variable-stability helicopter suggest that, for hovering and low-speed flight tasks:

1) There was no discernible difference in handling qualities among the three response-types evaluated (attitude command/attitude hold, rate command/attitude hold, and pure rate command). This result indicates that attitude hold is not essential for low-speed operations in an environment where the pilot can devote full attention to flying the aircraft.

2) There was a strong correlation between bandwidth frequency and pilot rating. The data suggest that a higher bandwidth is required in roll than in pitch. For satisfactory (level 1) handling qualities, pitch bandwidths greater than about 1 rad/s and roll bandwidths greater than about 2 rad/s were required.

3) Of the four tasks flown (precision hover, vertical landing, sidestep and dash/quickstop), the landing task was the most demanding overall, and hover was the least demanding.

4) Comparison with results from a piloted simulation of V/STOL shipboard landings shows the landing task in flight to require much lower bandwidths and result in a much lower variation in pilot ratings.

For operations with an integrated four-axis sidestick controller:

1) For the multi-axis tasks (dash/quickstop and sidestep), attitude command/attitude hold resulted in unsatisfactory (level 2) handling qualities. Rate was preferred slightly over rate command/attitude hold, but both received level 1 ratings as long as the bandwidths were sufficiently high.

2) The variations in pilot ratings with bandwidth were very similar, in general, to those for the conventional controllers. Similar levels of bandwidth were required for level 1 ratings.

3) The pilots were less sensitive to changes in handling qualities with the sidestick than with the conventional controls. When handling qualities were good, the conventional arrangement was favored, but as handling qualities degraded, the pilots preferred the sidestick controller.

4) An inherent shortcoming in the vertical response with the sidestick caused degraded response in this axis. The pilots were instructed to ignore this shortcoming in their evaluations, and these conclusions must be weighed in that context.

Acknowledgments

The flight experiments reported in this paper were conducted by the National Aeronautical Establishment, National Research Council, Ottawa, Canada, in support of an international effort to provide data for an upgrade to MIL-H-8501A (Update 8501). Mr. Murray Morgan was the project engineer. Systems Technology, Inc., cooperated through Contract NAS2-11304 from the U.S. Army Aeroflightdynamics Directorate, Moffett Field, California. Mr. Chris L. Blanken was the Army contract monitor and Mr. Roger Hoh was the STI project engineer. The test pilots were Messrs. Murray Morgan, Dan Sattler, and Stan Kereliuk of the NAE; Lt. Col. Mike Stortz from the U.S. Marine Corps; Mr. Trevor Egginton from Westland Helicopters, and Mr. Roger Hoh from Systems Technology, Inc. The authors are indebted to the test pilots for their time and careful evaluation of the configurations, and to Mr. Keith Davidson, safety pilot at the NAE.

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