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FLIGHT INVESTIGATION OF THE TRADEOFF BETWEEN AUGMENTATION AND DISPLAYS FOR NOE FLIGHT IN LOW VISIBILITY

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SUMMARY

The missions proposed for the next generation helicopter involve requirements to operate in essentially zero visibility in the nap-of-the-earth (NOE) environment. Such operations will require the use of pilot vision aids, which gives rise to the question of the interaction of such displays and the required aircraft handling qualities. This research was conducted to: 1) investigate the required visual cueing for low speed and hover, and 2) determine if an increase in stabilization can effectively be used to compensate for the loss of essential cues. Two flight test experiments were conducted using a conventional helicopter, and a variable stability helicopter, as well electronically fogged lenses and night vision goggles with daylight training filters. The primary conclusion regarding the essential cues for hover was that fine grained texture (microtexture) is more important than large discrete objects (macrotexture), or field-of-view. The use of attitude command augmentation was found to be effective as a way to makeup for display deficiencies. However, a corresponding loss of agility occurred with the tested attitude command/attitude hold system resulting in unfavorable pilot comments. Hence, the favorable control display tradeoff must be interpreted in the context that the best solution would be to improve the vision aid. Such an improvement would require an increase in the visible microtexture, an advancement in display technology which is unlikely to be available in the foreseeable future. Therefore, a criterion was developed to systematically evaluate display quality, and the associated upgrade in required stabilization as a function of increasingly degraded visual cues.

I. INTRODUCTION

The next generation helicopter must be able to operate at night, and in poor weather in the nap of the earth (NOE) environment to achieve adequate combat effectiveness. This gives rise to two critical issues, 1) collision avoidance with fixed objects, and 2) control and stabilization. In this paper, a criterion is developed specifically to address the control and stabilization issue for use in a revised rotorcraft handling qualities specification to supersede Mil-H-8501A (Ref. 1). The impact of displays on handling has never been accounted for in a handling qualities specification, and hence the proposed methodology is new and relatively untested. However, it is well supported by the theory of closed loop pilot vehicle analysis (Ref. 2), as well as data from two flight test experiments, and a ground-based piloted simulation (NASA Ames Vertical Motion Simulator). The criterion addresses the additional automatic flight control system (AFCS) stabilization that may be utilized to makeup for certain display deficiencies in the NOE environment. Improved displays which allow low workload NOE operations in very low (essentially zero-zero) visibilities, might someday obviate the need for such a criterion. However, such a quantum advance in display technology seems unlikely in the foreseeable future.

Both collision avoidance, and control and stabilization are addressed in the present version of the proposed specification revision which exists in the form of a U.S. Army Aeronautical Design Standard (ADS 33, see Ref. 3*). Collision avoidance is specified in Ref. 3 terms of three-dimensional maneuvering envelopes. The manufacturers are required to demonstrate that these envelopes do not fall outside the visual field of the available displays and/or vision aids. In the present paper however, we shall focus our attention on the development of a criterion for control and stabilization in the presence of degraded visual cueing.

II. BACKGROUND AND SUPPORTING THEORY

1. Development of the Specification Methodology

The proposed revision to the Ref. 1 specification will be heavily couched in automatic flight control system terminology in recognition of the fact that modern rotorcraft will utilize full authority fly-by-wire flight control systems. For example,

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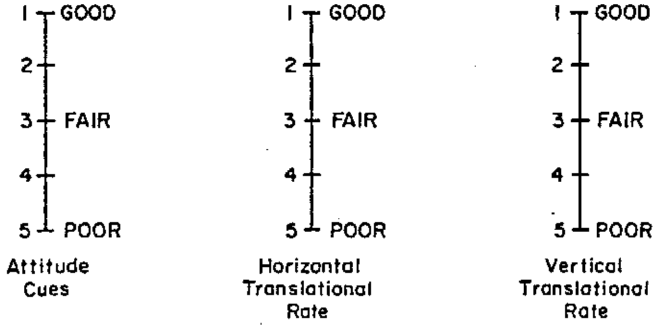
many of the criteria in ADS 33 (Ref. 3) are written in terms of "Response-Types" which classify the generic rotorcraft responses to control and disturbance inputs. The Response-Types defined in ADS 33 are Rate, Rate Command Attitude Hold (RCAH), Attitude Command Attitude Hold (ACAH), and Position Hold (PH). An incidental, but nontheless important byline to this is that the AFCS architecture is not specified. For example, the responses of a proposed acceleration command system were shown to fall in the ACAH Response-Type category.

In good visual conditions, most required tasks can be performed with a Rate Response-Type (see Ref. 3). In conditions of degraded visibility, and/or when the pilot must rely on vision aids, some of the cues required for control and stabilization are lost. The specification methodology is based on requiring additional AFCS stabilization (upgrade in Response-Type in spec terminology) in such conditions.

The basic elements required to carry out the proposed specification methodology are quantitative definitions of, 1) the Response-Types and, 2) the pilot's "usuable cue environment" (UCE). A viable definition for the UCE should include the following features.

- It should depend on the pilot's ability to maneuver aggressively. In particular, it should not depend on the pilot's qualitative assessment of the usable cues. Experience gained during the Ref. 4 testing has shown that there is a strong tendency to overestimate the usefulness of available cues in a static environment.
- It should include the effects of all available vision aids and displays, including superimposed display symbology.
- It should not depend on the level of stabilization, since that is separately accounted for in the specification.
- Since quantitative metrics are not available, the UCE must be determined from a scale based on qualitative pilot evaluations. To the extent possible, the scale should:
    - -- Utilize adjectival phrases with equivalent semantic meanings to all evaluation pilots.
    - -- Be linear (e.g. a visual environment which is twice as bad should receive double the numerical rating).
    - -- Have low variability. Repeat evaluations, and evaluations for several pilots should result in rating scores with a low standard deviation.

The visual cue rating (VCR) scale in Fig. 1 was developed to satisfy these requirements. The words "good, fair, and poor" were shown to have low variability, to be linear, and to have essentially equivalent semantic meanings in the rating scale experiments described in Ref. 5. The definitions of cues given below the scales define maneuvering in terms of aggressive, moderate, and gentle corrections. These were developed from the pilot-vehicle analysis considerations presented in the following subsection, and have been tested and refined during the flight test experiments discussed herein.



Definition of Cues

X = Pitch or roll attitude and lateral, longitudinal, or vertical translation rate.

Good X Cues: Can make aggressive X corrections or changes with confidence.

Fair X Cues: Can make only moderate X corrections or changes with confidence.

Poor X Cues: Only small and gentle corrections in X are possible, and consistent precision X control is not attainable.

Figure 1. Visual Cue Rating (VCR) Scale

2. Supporting Pilot-Vehicle Analysis Considerations

Performance of low speed NOE maneuvering requires that the pilot be able to perceive certain aircraft states with sufficient clarity to use them, and their derivatives, as feedbacks. For the conventional unaugmented helicopter, these feedbacks consist of aircraft attitude, and its derivative (angular rate), and aircraft position, and its derivative, translational velocity. This is illustrated in Fig. 2a, where the pilot is modeled according to conventional pilot-vehicle analysis (see Ref. 2). If attitude stabilization (attitude command attitude hold, ACAH) is provided, the block diagram in Fig. 2b would apply. The stabilization resulting from various combinations of pilot and/or SCAS equalization is summarized in terms of root loci in Fig. 3, which results in the following observations for a typical rotorcraft which may be characterised by the classical hover cubic.

- From Fig. 3a, it is not possible to maintain a stable hover without attitude stabilization.
- From Fig. 3b, closure of the attitude loop without lead, is conditionally stable, and is limited in terms of maximum achievable damping. The position loop closure requires considerable lead i.e., the translational rate cues must be good.
- From Fig. 3c, the use of lead in the attitude loop allows a much better inner loop around which to close the position loop. As a result, the position loop closure requires less lead i.e.,the translational rate cues only need to be fair. Note that the attitude loop lead carries into the outer position loop as a consequence of the assumption of a series pilot model (Fig. 2a).
- Figure 3d, represents the situation where ACAH augmentation is employed (Fig. 2b). A stable position loop closure is possible over a wide range of pilot gain, and the required position loop lead is only moderate i.e., only fair translational rate cues are required. This root locus also applies to the nonaugmented case, if a parallel pilot model structure is assumed (see Ref. 2).

The point to be made is that a good attitude loop closure alleviates the requirement for lead in the position loop. On this basis, an attitude command attitude hold SAS would be expected to compensate for degraded translational rate cues; a result which forms the foundation for the proposed criterion. The visual cue rating scale in Fig. 1 is intended to provide some measure of the available cues ("usable cue environment") for controlling attitude and position. The ability to develop attitude lead is believed to require high quality visual cueing. Based in the attitude root loci in Figs. 3b and 3c. the, lack of such lead results in a conditionally stable response, one which would preclude aggressive attitude corrections. Hence, the visual cue scale in Fig. 1 is based on the ability to make aggressive corrections in attitude. This is carried over to the definition of horizontal and vertical rate cuess based on similar reasoning. It was found to be extremely important in the experiment described in Section III that, in making VCR evaluations, the pilots avoid qualitative assessments of a display or vision aid that deviates from the Fig. 2 definitions.

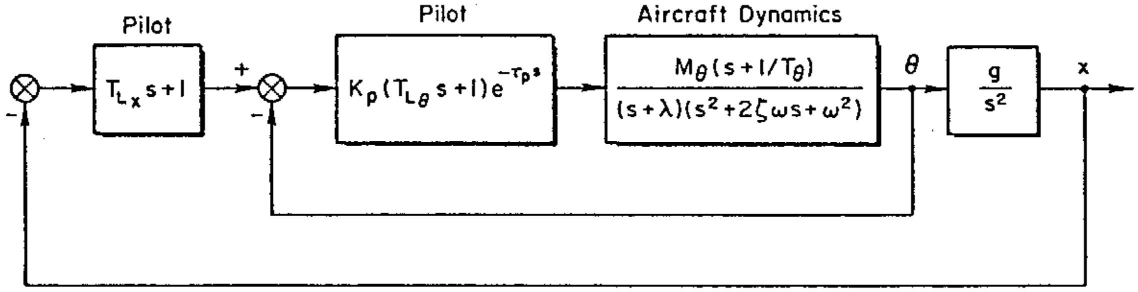
III. EXPERIMENTAL DATA

1. Visual Cueing Experiment

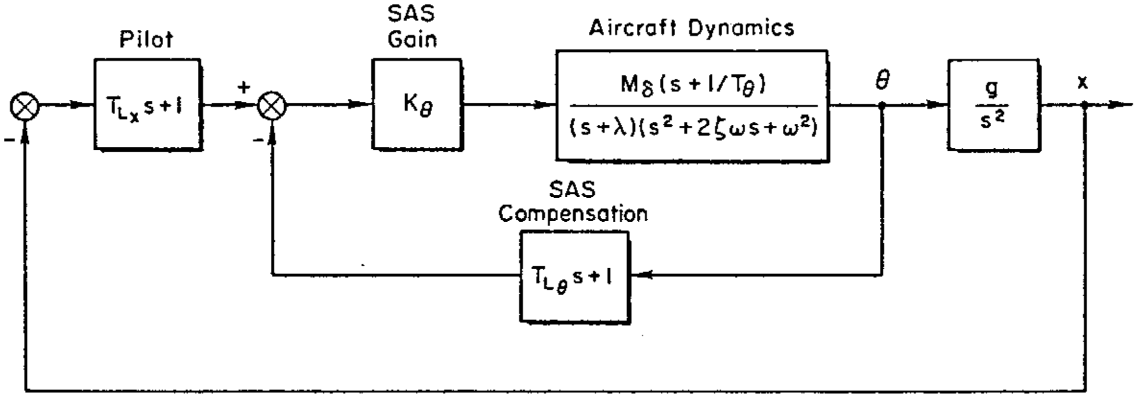
The fundamental visual cues required to perform low speed and hover maneuvering in the NOE environment are not well understood. Knowledge of these essential cues is required for the development of pilot displays for low or zero visibility operations. This flight test experiment (described in detail in Ref. 4) provides some insight into the necessary cues for control and stabilization and the results are summarized in this section as supporting data for the criterion to be developed subsequently in Section IV. The primary variables in the Ref. 4 flight tests were the field-of-view, the amount of visible macrotexture (large objects) and microtexture (fine-grained detail). Six different fields of view were tested, varying from a small (10 deg X 10 deg) forward looking window to larger windows (see Fig. 4) which had essentially no restrictions to peripheral vision.

The visible texture was varied by conducting the tests over two marked courses (Fig. 5) on a dry lakebed, and by using special electronically fogged lenses to remove the visible microtexture (cracks in te lake bed). The scope of the experiment did not allow quantitative measurements of the fogged lenses in terms of the modulation transfer function (see Section V). An estimate of the pilots' visual environment with the lenses fogged was obtained from a standard eye chart (Landolt rings) set up at the test site. The pilot's vision with the lens fogged tested from 20/20 to 20/40, even though the pilots generally agreed that the cracks in the lakebed were removed as usable visual cues. The details of visual cueing are discussed in Section V, where it is shown how it is possible to test 20/20 on a standard eyechart and still not be able to utilize small detail as a usable cue due to inadequate depth of modulation.

The visual cue ratings (VCRs from Fig. 1), and Cooper- Harper handling qualities ratings are plotted against the variations in field-of-view in Fig. 6. The following observations can be made from this data.

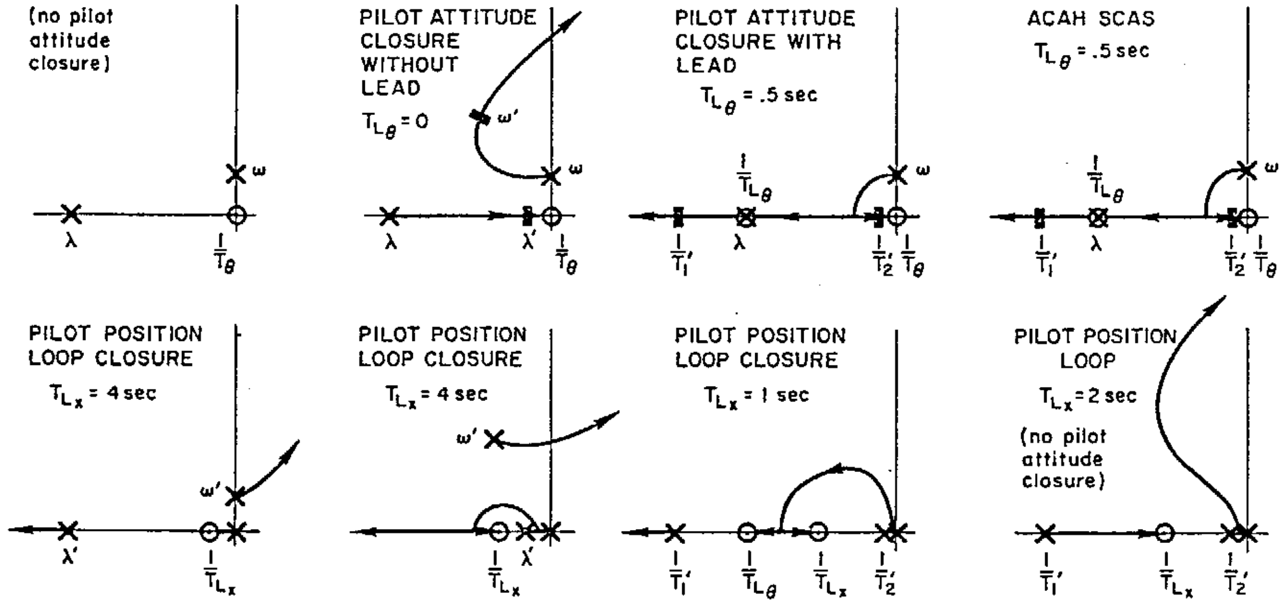


a) Unaugmented Helicopter



b) Attitude Augmentation

Figure 2. Piloted Closure for Hover



a) No Attitude Closure

Unstable

Results from poor attitude cues without SCAS

b) Attitude Closure Without Pilot Lead

Requires large T_{L_x}

Requires fair attitude cues and good translational rate cues

c) Attitude Closure With Lead in Attitude Loop

Reduced requirement for T_{L_x}

Requires good attitude cues and fair translational rate cues

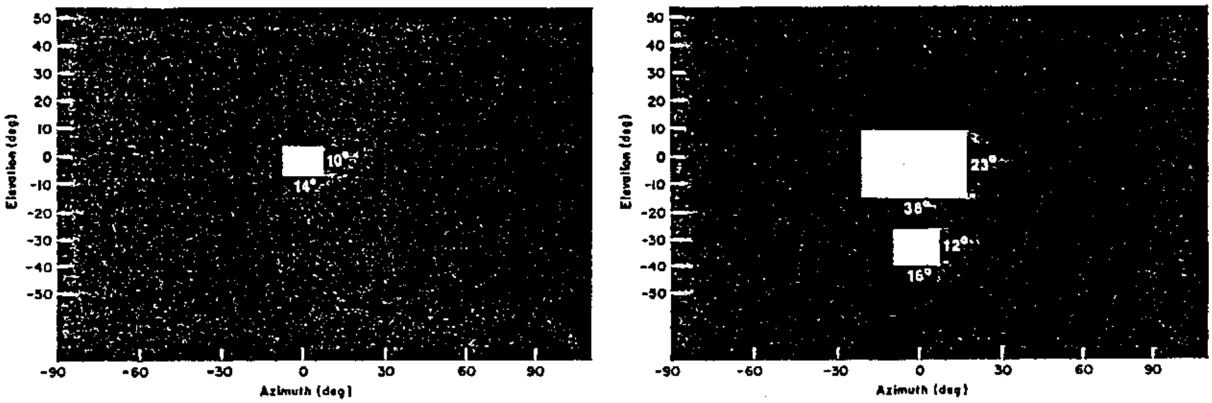
d) ACAH SCAS - No Pilot Attitude Closure

Requires only moderate T_{L_x}

Attitude cues may be fair to poor

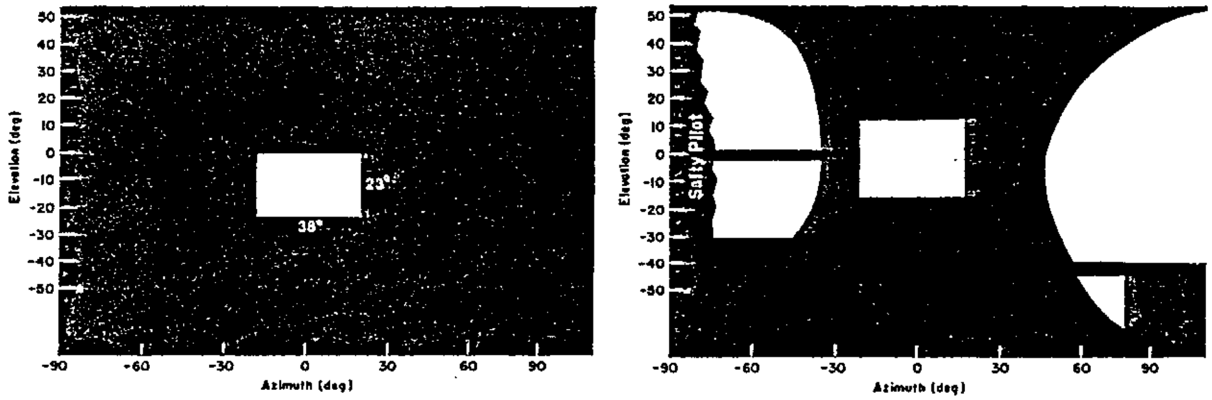
Translational rate cues only need to be fair

Figure 3. Tradeoff Between Attitude and Translational Rate Feedbacks Required for Stable Hover



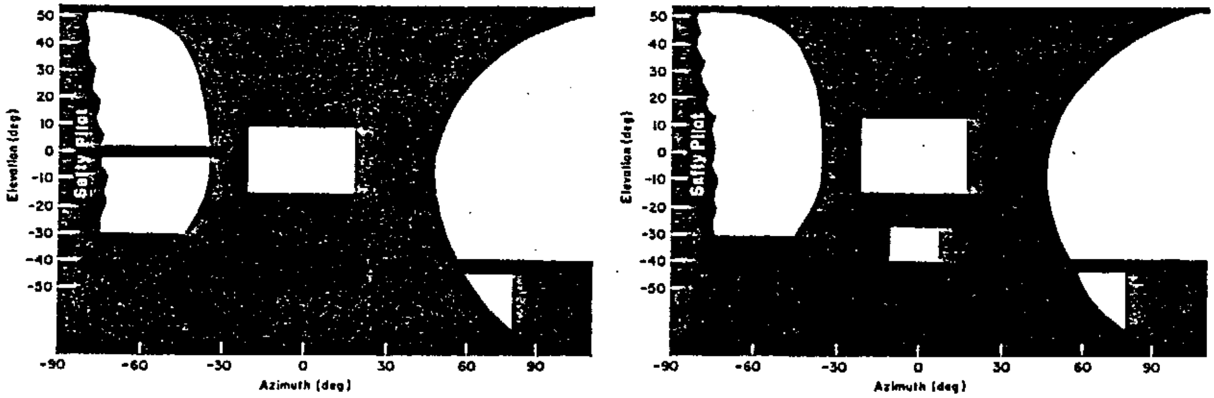
(a) Variations in field-of-view — configuration 1 (narrow upper front to evaluate potential displays)

(d) Variations in field-of-view — configuration 3 (nominal upper front plus lower front to investigate effect of thin window)



(b) Variations in field-of-view -- configuration 2 (nominal upper front to simulate NASA Ames VMS front monitor)

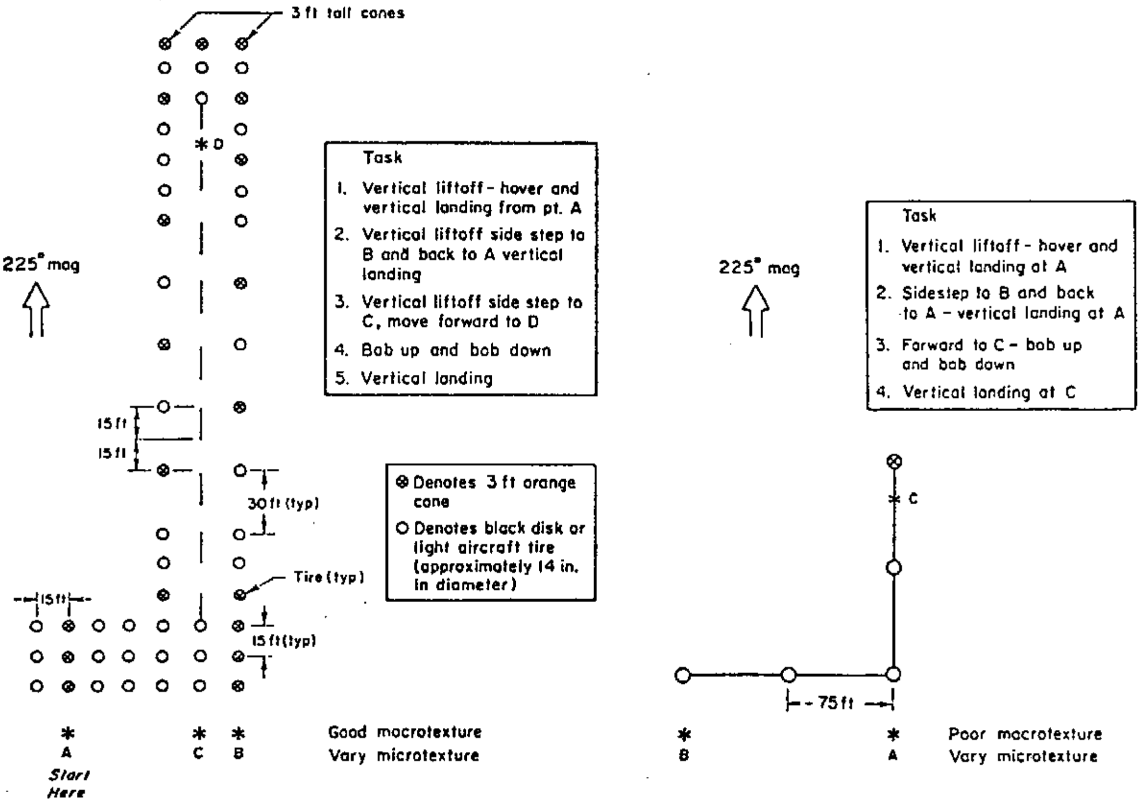
(e) Variations in field-of-view -- configuration 7 (wide upper front plus sides)



(c) Variations in field-of-view — configuration 6 (nominal upper front plus sides to investigate effect of thin window)

(f) Variations in field-of-view — configuration 8 (wide upper front + lower front + sides)

Figure 4. Field-of-View Variations in Reference 4 Experiment



a) Test Site One

b) Test Site Two

Figure 5. Test Sites in Ref. 4 Experiment

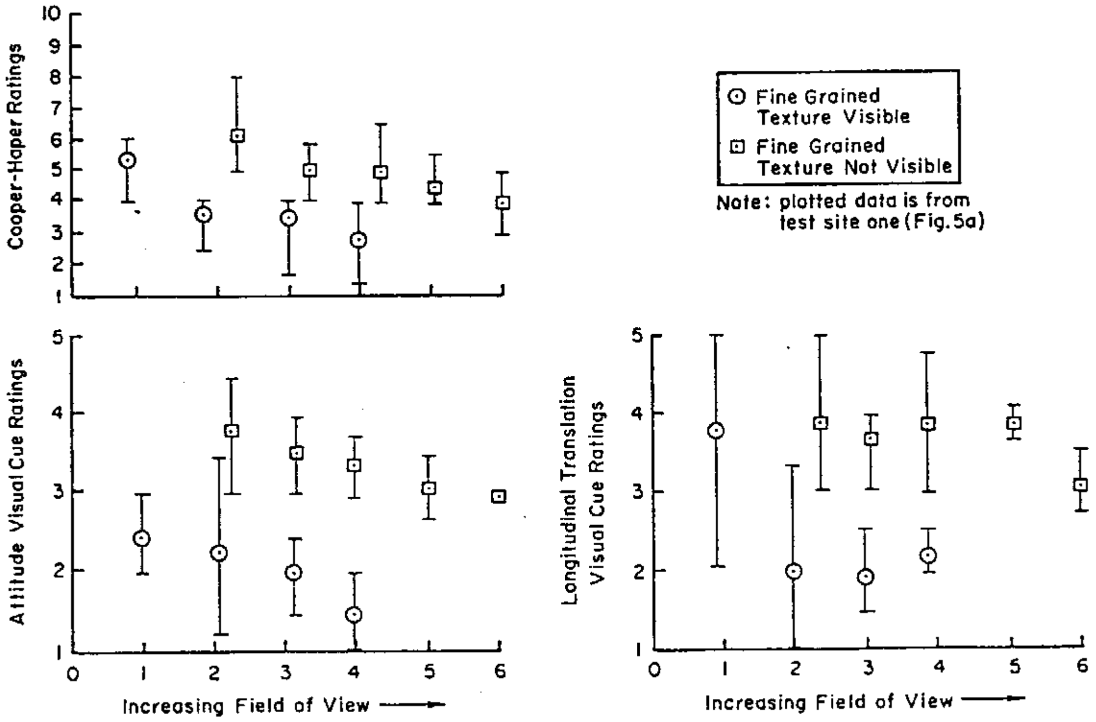
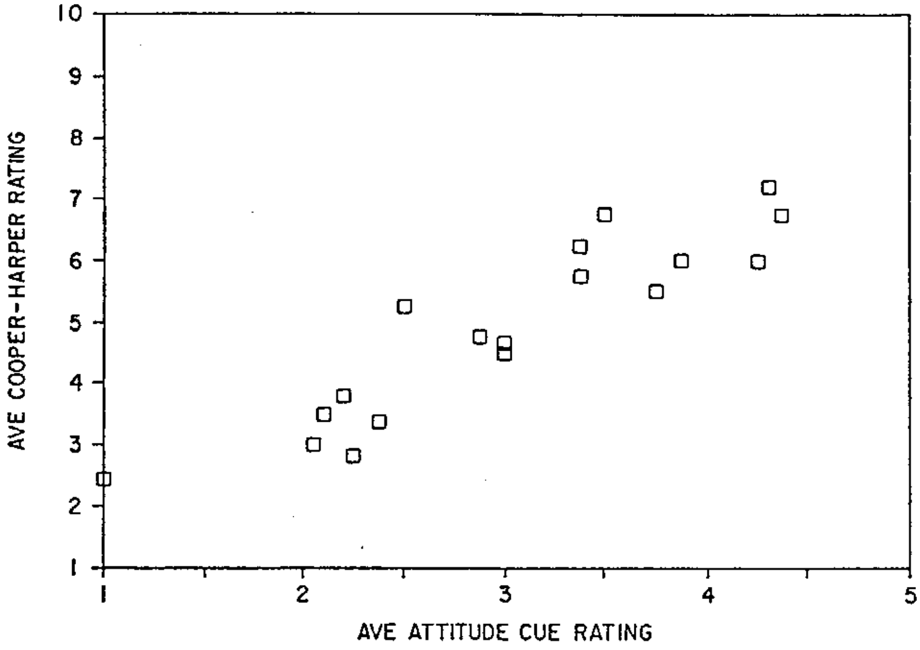


Figure 6. Effect of Field-of-View and Microtexture Variations in Ref. 4 Experiment

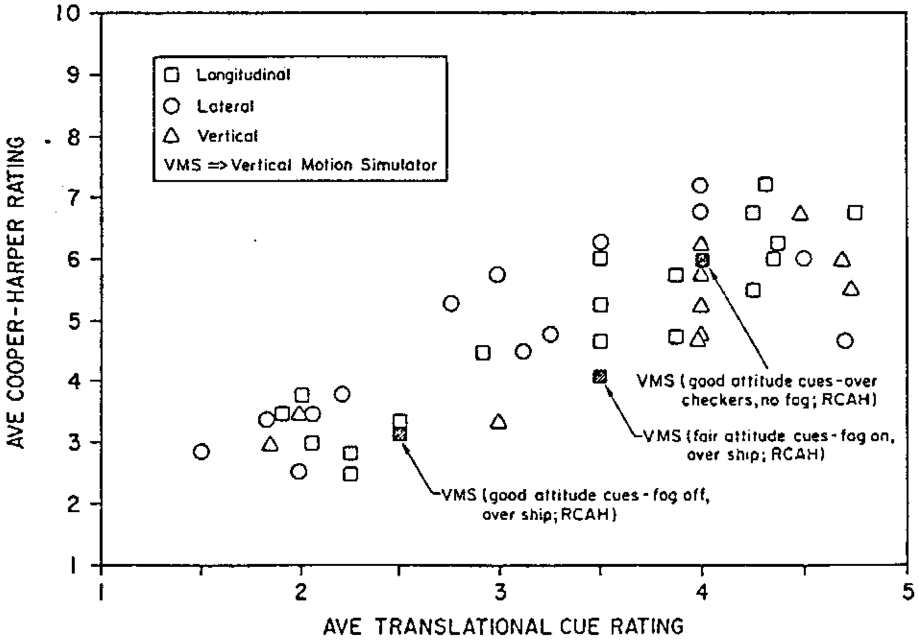
- Visible microtexture is an important visual cue for control and stabilization.
- Increasing the field-of-view beyond 38 deg X 23 deg (Configuration 2 in Fig. 4) does not result in significant improvements in Cooper-Harper or vsual cue ratings. An increase in field-of-view would, of course, be desirable for navigation and orientation, however, the results of this experiment indicate that it would be undesirable to increase the field-of-view of a pilot vision aid at the expense of resolution (visible microtexture).

The Fig. 6 data includes only the results obtained on Test Site one (Fig. 5a) which was rich in macrotexture. The results from Test Site two (Fig. 5b), which was devoid of macrotexture, were essentially the same. Hence, macrotexture was found to be of secondary importance to microtexture in terms of cues required for stabilization and control.

The averaged visual cue ratings are plotted against the averaged Cooper-Harper ratings in Fig. 7 to examine the effect of degraded visual cueing on handling qualities. These results show that:



a) Attitude



b) Translational Rate

Figure 7. Variation in Average Visual Cue Rating For Attitude and Translational Rates With Average Cooper-Harper Rating (Data from Ref. 4 and 8)

- The test helicopter, a Hughes 500D, was given Level 1 ratings when the VCRs were 1.5 or better.

- The handling qualities ratings steadily degraded as the VCRs increased, which validates the trend predicted from the analysis in Fig. 3.

Some visual cue ratings were taken from a moving base simulation conducted on the NASA Ames VMS and these are also plotted in Fig. 7b. These data show that the trend of the degredation in Cooper-Harper ratings with increasing translational rate VCRs agrees reasonably well with flight test. The attitude VCRs were judged to be good for all cases on the simulator, indicating that the trends in Fig. 7b are not dependent on simultaneous degredation of attitude and translational rate cues.

The VCR scale (Fig. 1) not only plays a significant role in the proposed criterion, it also provides a quantitative metric for comparison of competing displays or vision aids. As noted earlier, the validity of such a scale depends on its ability to produce ratings with low variability within and amongst pilots. The variability of the Fig. 1 scale for the experimental data from Ref. 4 is shown in the cumulative distribution plot in Fig. 8, where the ordinate is the percentage of total VCR ratings with a standard deviation less than or equal to a given value on the abscissa. This data included over 200 separate evaluations. Based on this plot, it would be expected that the standard deviation in the VCR ratings in a given experiment would not exceed 0.75 more that 0.8% of the time. This is a reasonable validation of the scale, and is the basis for a Ref. 3 specification requirement that the standard deviation in the ratings not exceed 0.75. Such a deviation would be reason to suspect the existence of an anomalous set of ratings such as may be caused by a preconceived mind-set by one of the evaluation pilots. In such cases, the procuring activity may elect to assign additional pilots, or to make a decision based on other factors (such as eliminating one pilot's ratings, or emphasizing the pilot comments more than the numerical ratings).

2. Control-Display Tradeoff Experiment

An experiment was conducted to validate the analytically based hypothesis, that the addition of attitude stabilization would be effective as compensation for some loss in visual cues. If valid, such a hypothesis would allow for the possiblity that augmentation can be effectively utilized to make up for less than ideal displays and/or vision aids. This is especially useful in light of the fact that the fine-grained texture (microtexture), found to be an essential cue for stabilization and control in the above discussed visual cueing experiment, is very difficult to incorporate into displays and vision aids. For example, the usable microtexture is somewhat limited for forward looking infrared (FLIR) displays, computer generated imagery (CGI), and light intensifier systems or night vision goggles (NVG). This is further exacerbated by the tendency to increase the field-of-view at the expense of microtexture, a trend that improves positional awareness, but at the expense of control and stabilization.

The experiment discussed herein utilized a variable stability helicopter (Canadian National Aeronautical Establishment (NAE) Bell 205A), and night vision goggles as a representative pilot vision aid. The night vision goggles were a current state-of-the-art system (PVS-6). However, safety considerations dictated that they be used in the variable stability aircraft only in daylight conditions. Night conditions were simulated using variable density training filters which allowed the simulation of conditions varying from a full moon to a very dark night such as might exist in a rural area with a solid overcast. The following factors arise from the use of daylight filters to simulate the night environment.

- Pilots experienced with the PVS-6 night vision goggles indicated that they are much easier to use in the real night environment. Hence, the results of this study must not be used as a basis for an evaluation or comparison of the night vision goggles.

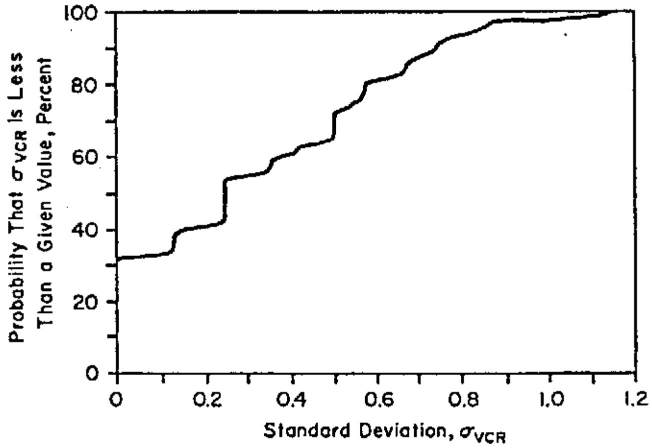


Figure 8. Cumulative Distribution of Standard Deviations of Visual Cue Ratings Given by Pilots

- The available texture depended greatly on the lighting conditions (overcast vs. sunny).
- Any direct glare from the sun severely degraded the visual scene.

Another factor which should be taken into account is the lack of available time to sufficiently train evaluation pilots to fly the night vision goggles. Most pilots were allowed about 2 hours of familiarization before conducting formal evaluations, which is substantially less than the time allotted by the U.S. Army to qualify for actual night vision goggle operations.

The variable stability Bell 205A was configured to simulate a rate augmented helicopter, and a helicopter with Attitude-Command-Attitude-Hold (ACAH) augmentation. Both configurations were tested to be Level 1 with no restriction to vision (Cooper-Harper handling quality ratings equal to or less than 3.5) in a previous handling qualities experiment (best Rate and ACAH systems from Ref. 6). The task was essentially identical to that used in Ref. 6 except that a bob up/down, and hover turn were added, see Fig. 9.

The test procedure involved setting the variable density filters, while sitting in the helicopter, at a calibration site wherein a standard eyechart was mounted 20 feet from the evaluation pilots head. The filters were run at two settings; wide open (pilots usually reported this as 20/70 in terms of visual acuity), and at a setting which resulted in a visual acuity of 20/85. To put this in an operational context, the PVS-6's tested between 20/50 and 20/60 on a full moon night, and about 20/85 on a dark overcast night with some distant glow visible from airport runway lights (it was not possible to see the eyechart at all with the unaided eye).

Two test sites were utilized to further vary the visual environment. One site was over a large, flat, grassy field, and the other in a swampy area with large clumps of weeds which provided additional microtexture. Finally, tests were run with and without snow cover, on sunny and cloudy days, and on windy and calm days (most were calm).

A total of seven evaluation pilots participated in the experiment, although only four had enough familiarization time to achieve consistent, ratings. Visual cue ratings (VCRs from Fig. 1) and standard Cooper-Harper handling qualities ratings were obtained for the Rate augmented configuration, whereas only Cooper Harper ratings were obtained for the ACAH configuration. Visual cue ratings were not obtained for the ACAH cases because the use of such augmentation obviates the need for the critical cues. The pilots were required to fly the Fig. 9 test course at least three times before assigning the ratings, and recording their comments. This resulted in about 20 minutes of evaluation time which included 12 vertical landing, 3 sidesteps, quickstops, bobup/downs, turns about a point, and precision hovers. Separate Cooper-Harper ratings were given for each of these maneuvers.

The VCR and Cooper-Harper rating results were analyzed with a view toward answering the following questions.

- What is the interdependence between the three components of visual cues in Fig. 1 (attitude, horizontal and vertical translational rates)?
- To what extent does ACAH alleviate the degradation in handling qualities associated with a degraded visual environment?
- What combination of VCRs causes a Level 1 (Cooper-Harper 1 to 3.5) baseline Rate augmented aircraft, to become Level 2 (Cooper-Harper 4 to 6)?

PILOT TASKS

1. Precision Hover and Vertical Landing at A
2. Hover turn about A at constant radius
3. Rapid sidestep to B – stabilize while pointing at B' – and return to A
4. Repeat 1
5. Quickstop to C
6. Bob up/down over C
7. Land at C
8. Return to A
9. Repeat 1-8 three times
10. Give ratings

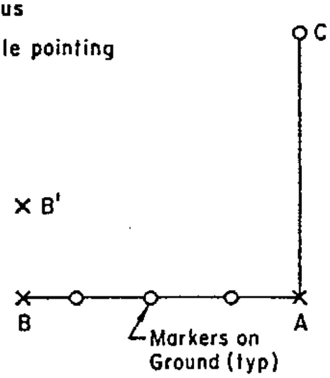


Figure 9. Test Course and Tasks Used in Night Vision Goggle Experiment (Also used in Ref. 6)

- Over that range of VCRs does the addition of ACAH upgrade the Cooper-Harper ratings from Level 2 (for the baseline Rate augmentation) to Level 1?

Each of these questions is addressed in the following paragraphs. Unless specifically noted, only data taken in calm conditions have been included in the analysis.

Interdependence Between Visual Cue Ratings

The interdependence between the three components of the Fig. 1 visual cue rating scale can be examined from the VCR rating data presented in Fig. 10 for Rate augmented cases with night vision goggles. Here it is seen that the vertical and horizontal translation cues are highly correlated ($R^2 = .84$) whereas the translation and attitude cues are relatively independent ($R^2 = .38$)*. A linear regression fit to the data is also plotted in Fig. 10. On this basis, the remainder of the analysis of the data is based on the attitude and horizontal translation cue rating (i.e., vertical translation cues are not included as an independent variable in the analysis).

Comparison Between Rate and ACAH In A Degraded Visual Cue Environment

The Cooper-Harper handling qualities ratings are plotted vs. the horizontal translation visual cue ratings for each of the tested maneuvers in Fig. 11. The following observations can be made from this rating data and the associated pilot commentary.

- The baseline Rate augmented configuration (triangles) exhibit a tendency toward increasingly inconsistent and degraded Cooper-Harper ratings with increasing VCR. This is consistent with the data from the visual cue experiment discussed in the previous section (see Fig. 7 and Ref. 4).
- Configurations with ACAH augmentation are given Cooper-Harper ratings between 3 and 4 up to a VCR of 4.5 for all maneuvers except the quickstop and bob-up/down. The quickstop received Level 2 ratings in the Ref. 6 experiment (no restriction to vision) due to the lack of agility inherent to the ACAH augmentation as mechanized. All pilots noticed problems in the bob-down with night vision goggles due to the lack of visible microtexture at altitudes above 10 to 20 ft. This resulted in a distinct lack of altitude and altitude rate awareness which was not alleviated by the ACAH augmentation (nor was it predicted to in the pilot-vehicle analysis in Fig. 3).
- The ratings for the ACAH cases, while better that rate cases in the degraded visual environment, did not reflect ideal conditions (i.e., Cooper-Harper ratings were 3 to 4). This might be improved with an optimized ACAH augmentation, however, it is suspected that the use of such augmentation is less attractive than restoring the visual conditions via improved displays. Even though ACAH allows the pilot to operate in degraded visual conditions, there is a distinct loss of aggressiveness due to the nature of ACAH, and to the above noted problems in the height axis. However, displays with adequate microtexture for stabilization and control, combined with an adequate field-of-view for positional awareness are not expected to be available in the near future. Hence, the use of augmentation to make up for display deficiencies represents the only compromise.

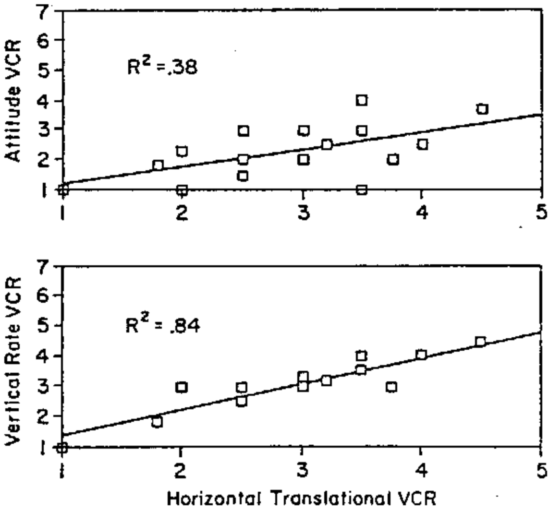


Figure 10. Interdependence between Visual Cue Ratings

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*R is the correlation coefficient and $\sqrt{1 - R^2} = 0$ represents perfect correlation.

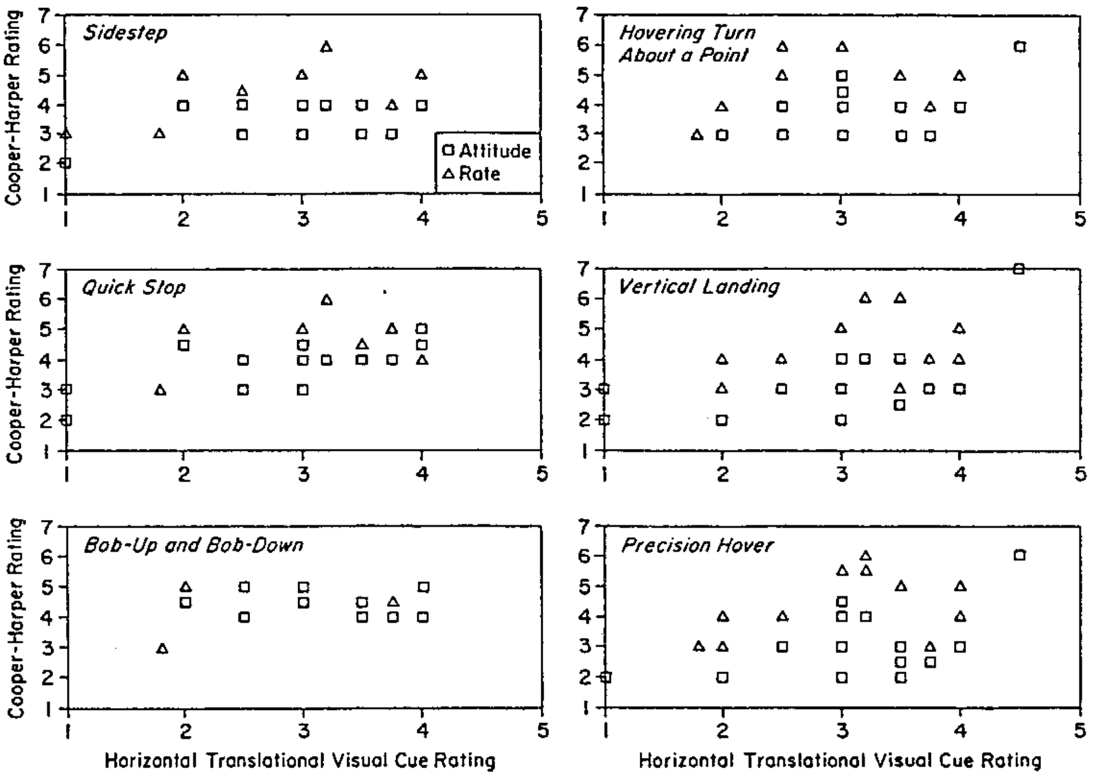

Figure 11. Cooper-Harper Ratings vs. Horizontal Translational Cue Ratings

The results shown in Fig. 11a through 11d effectively validate the basic hypothesis formulated in Fig. 3 (i.e. attitude augmentation can be used to offset degraded attitude and translation visual cues). The Cooper-Harper ratings for ACAH might have been even better if the stick force gradients were somewhat higher. This was noticed late in the tests as a result of continuing comments by the pilots that the ACAH case tended to "buck and shuffle" in response to pitch commands. It was then noted that the force gradient was a factor of four less than that used in a previous ground-based simulation (Ref. 8) conducted on the NASA Ames Vertical Motion Simulator (.5 lb/in in flight and 2.0 lb/in in the simulation). Increasing the gradients, and modifying the controller inertia and friction empirically, resulted in considerably improved pilot acceptance of the ACAH case. Interestingly, the lower stick force gradient was not noticed by 5 different pilots in the previous handling qualities tests (Ref. 6) suggesting that higher gradients are desired when degraded vision is a factor.

Effect of Visual-Cue Ratings on Cooper-Harper Ratings

The effect of visual cue ratings on Cooper-Harper handling qualities ratings suggested by* the experimental data was estimated by the application of a multiple linear regression. This resulted in the following empirical relationship between handling qualities (HQR) and visual cues (VCR) for rate augmentation.

$$HQR = 0.89 + 0.89\ VCR_{\theta} + 0.60\ VCR_{x}$$

This regression fit was accomplished using the current experimental data for night vision goggles with Rate augmentation, and the data taken from the Ref. 4 experiment (discussed in III.2) resulting in a total of 89 observations. The correlation coefficient for this fit is .83 which statistically indicates correlation at substantially better than the 99% level of significance (Ref. 9). The estimated and actual ratings are plotted in Fig. 12, where it is seen that the data spread about the line of perfect correlation is reasonable up to ratings of about 7. Beyond this value, the linear fit is nonconservative. However, the complexity of a multiple nonlinear regression seems unwarranted, since only the data up to a rating of 6.5 is used in the subsequent criterion development.

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*In the Ref. 4 experiment, the pilots gave a composite Cooper Harper rating for the full test course (Fig 5), whereas in the present experiment, separate ratings were given for each task (see Fig. 11). The multiple regression was done using an average of the precision hover and the landing Cooper Harper ratings.

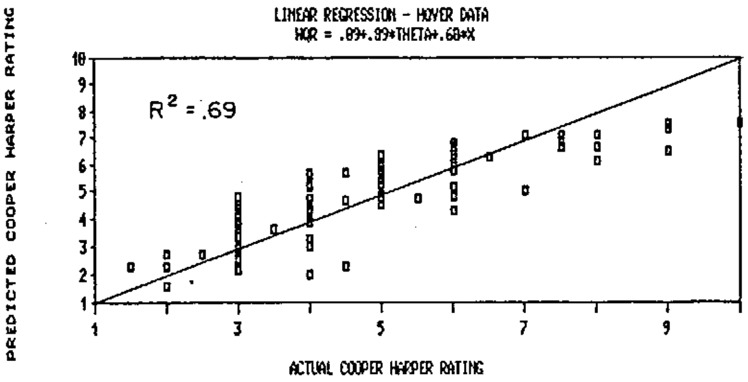


Figure 12. Linear Multiple Regression for all cases without ACAH (from both experiments) $R^2 = 0.69$, 89 observations, RMS error of Cooper-Harper Rating = 1.0

The data for Rate augmented and unaugmented configurations from both experiments are plotted on a grid of attitude VCR vs. horizontal translation VCR in Fig. 13. The dashed lines represent estimated Cooper-Harper handling qualities ratings (HQR) from the linear regression fit, and are seen to represent a reasonable (albeit conservative) separation between the pilot rating data. The data is separated at the 3.5 and 5.5 values of handling quality rating on the basis that the 3.5 line represents the classical Level 1/2 boundary in Mil-F-8785C (Ref. 10). The 5.5 line is based on the results shown in Fig. 13b, and the 6.5 line is Level 2/3 boundary in Mil-F-8785C.

The results shown in Fig. 13b indicate that the region defined by handling quality ratings of 3.5 to 5.5 for the baseline Rate Response-Types is mostly Level 1 for ACAH. All of the exceptions are barely Level 2 (rating of 4) and occurred in gusty wind conditions. As the visual conditions degrade beyond the line defined for HQR (Rate) = 5.5, the ACAH augmentation is seen to be ineffective as a means for maintaining Level 1 handling qualities. The 5.5 line is therefore a natural upper limit for a criterion which allows ACAH to compensate for a degraded visual cue environment.

IV. DEVELOPMENT OF CRITERION

Figure 13a suggests that the region below the HQR (Rate) = 3.5 line does not require additional stabilization, while Fig. 13b indicates that the region between that line and the HQR (Rate) = 5.5 line is Level 1 when ACAH augmentation is employed. A criterion suggested by these regions, with the following modifications, is given in Fig. 14.

- The regions have been modified to disallow extreme differences between attitude and translation VCR ratings as a means of compliance. This is to prevent, for example, a display with excellent attitude cues and poor translation cues from meeting the criterion.
- The region above the HQR (Rate) = 6.5 has been disallowed on the basis that it is unlikely that any augmentation can make up for such a major deficiency in visual cueing.

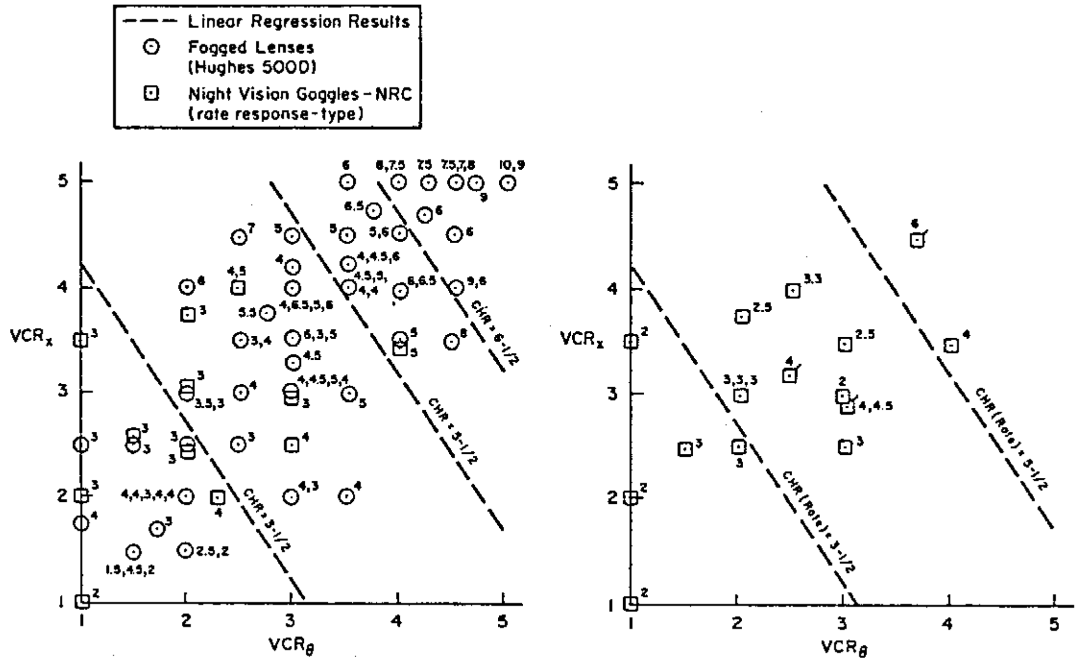
The regions established in Fig. 13 have been defined in term of four levels of usable cue environment (UCE) in Fig. 14. Each UCE level is utilized to set a requirement for a minimum Response-Type in Table 1. (The minimum response-types for the pitch and roll axes are shown in parenthesis in Fig. 14, below the UCE label). The justifiction for requiring Rate and RCAH for UCE=1, and ACAH for UCE=2, (Table 1 and Fig. 14) is based on the experimental data in Fig. 13. The justification for adding position hold in the UCE=3 region, is based on recent simulation data (not yet published) which showed that Level 1 ratings were possible with position hold, even when the pilot was preoccupied with other tasks in a very high workload environment. In addition, the simulator visual display (NASA Ames VMS) had a UCE of 2 (based on Fig. 7).

The Table 1 requirements for the yaw and height axis stabilization for UCE = 1 and 2 are based on what was used on the Bell 205 during the night vision goggle experiment. The Table 1 requirement for heading hold and altitude hold for UCE=3, is not supported by data at this time.

Application of the Criterion

The UCE ratings used in Table 1 must be obtained experimentally, using the VCR scale in Fig. 1, and conversion to UCE in Fig. 14. The process of obtaining the VCR ratings consists of an experimental evaluation of the proposed vision aids and displays, and must be conducted under certain specified conditions.

- The test aircraft must have a Rate or RCAH Response-Type. Additional stabilization would obviate the need for the cues that the display is being tested for.



a) Unaugmented and Rate Cases *b) ACAH Augmented Cases*

Figure 13. Correlation of Cooper-Harper Handling Qualities (HQR) and Visual Cue Ratings (VCR)

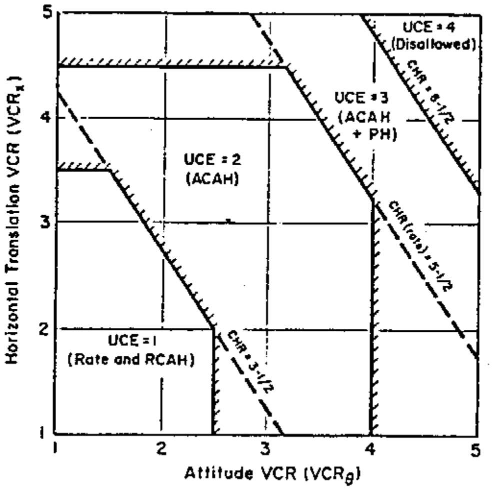


Figure 14. Definition of Usable Cue Environments and Minimum Allowable Response-Types

TABLE 1. REQUIRED UPGRADED RESPONSE-TYPE IN THE PRESENCE OF DEGRADED UCE — NEAR-EARTH OPERATIONS

AXIS OF CONTROL	RESPONSE-TYPE SPECIFIED FOR UCE=1	UPGRADED RESPONSE-TYPE IN THE PRESENCE OF DEGRADED UCE	
		UCE=2	UCE=3
Pitch and Roll	Rate	ACAH	ACAH + PH
	ACAH	ACAH	ACAH + PH
Yaw	Rate	Rate	RCDH
Height	Rate	Rate	Rate + RCHH

NOTES:

- ACAH — Attitude Command/Attitude Hold
- RCDH — Rate Command/Directional Hold
- PH — Position Hold or "hover hold"
- RCHH — Altitude Rate Command with Altitude Hold

- The test aircraft must be Level 1 in good visibility (i.e. the average handling qualities ratings must be 3-1/2 or better).
- At least 3 evaluation pilots must be used and their results averaged (hence the need for a linear VCR rating scale).
- The tests should be conducted in calm air.
- The tests should include precision hover, precision vertical landing, hover turns about a point, quickstops, and bobup and bobdown.
- The standard deviation of the VCRs should be less that 0.75 or additional pilots should be employed, or. the procuring activity may designate the required upgrade. The caveat is included to allow the removal of an anomalous rating which may occur, for example due to a pilot's preconceived notion regarding a particular display.

Note that it is not necessary, or even desirable, to test the display in the prototype aircraft. The handling qualitites of such an aircraft are rearely well known, the display may be ready for testing before the test aircraft, and it is not desirable to tie up a prototype test aircraft to evaluate displays.

V. REQUIREMENTS FOR IMPROVED VISUAL DISPLAYS

As noted above, the use of control augmentation to offset a degradation in visual cueing represents a compromise in which agility, and aggressiveness are sacrificed. A better, albeit not currently attainable, solution is to provide a display with adequate field-of-view and range for positional awareness, and microtexture for control and stabilization.

The implication of the results presented herein is that microtexture is an important cue which must be quantified in order to develop meaningful display requirements. Such quantification would be couched in terms of the modulation transfer function (MTF) which characterizes microtexture in terms of spatial frequency (Ω), and the modulation of the image (Ref. 11). The modulation of the image is measured as the difference in intensities between the peaks and the troughs across the spectrum in the visual field. Hence the contrast of the microtexture can be quantified in terms of the depth of modulation.

The resulting display requirements might appear as shown in Fig. 15. The upper limit of the required modulation depth is based on the maximum capability of the human eye as measured by Van Ness and Bouman (Ref. 12). The lower limit is an estimate since data are not available, Similarly, the desired range of spatial frequencies is a rough estimate, centered about the frequency of the cracks in the lakebed (at a range of 20 ft. from the pilot's eye) available on the test course in the Ref. 4 experiment (see Fig. 5b). The lower curve in Fig. 15 "explains" how some pilots achieve 20/20 visual acuity with the lenses fogged. That is, there was probably sufficient depth of modulation at a spatial frequency of one arc-minute to distinguish the letters on the eyechart, but not to acquire the information required for precision hover maneuvers.

Lacking precise, quantitative measures, such as the modulation transfer function, the VCR scale (Fig. 1) has been derived to measure the usable cue environment in terms of the ability to maneuver aggressively. The results of these experiments indicate that the scale is reasonably successful, and on that basis, is used to define the useable cue environment associated with a given display or vision aid. It was found that strict adherence to making assessments based on the level of achievable aggressiveness, as opposed to the pilot's qualitative evaluation of the available visual cues, is necessary when using the scale.

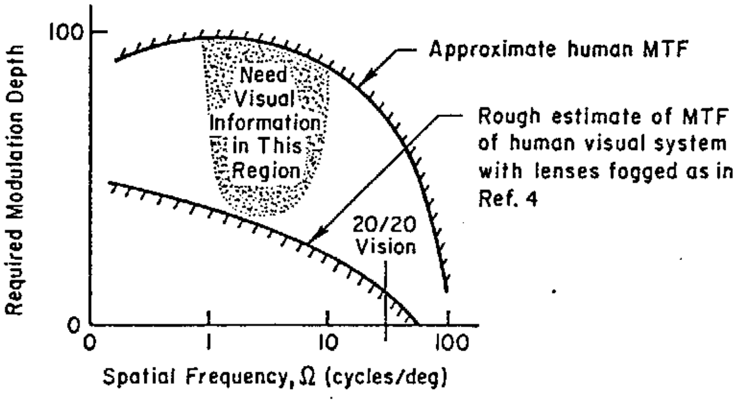


Figure 15. Proposed Generic Form of the Required Region of Visual Information for Hover

VI. CONCLUSIONS

The following conclusions summarize the development of the criterion developed in this paper.

- There is considerable evidence that microtexture is a primary cue for control and stabilization in hover and low speed flight.
- Field-of-view is of secondary importance to microtexture for control and stabilization, although it may be highly significant for positional awareness. Experimental data shows that the 30 deg field-of-view available on the PVS-6 night vision goggles is adequate for control and stabilization.
- It is possible to estimate the effectiveness of a display in terms of the visual cue rating (VCR) scale, and the resulting usable cue environment (UCE). These ratings may be used to assess the need for additional stability augmentation via the criterion developed herein.
- It is possible to makeup for losses in visual cues with attitude agumentation.
- The use of attitude augmentation to makeup for display deficiencies (i.e., insufficient microtexture) usually results in a loss of agility. Therefore, it is more desirable to improve the visual cueing than to makeup for a loss in such cueing via augmentation.
- It would be desirable to develop a more quantitative metric to evaluate displays. For example, the requirement could be stated in terms of an acceptable region on a grid of depth of modulation vs. spatial frequency. Research needs to be accomplished to determine this region.

REFERENCES

1. Anon, Military Specification -- Helicopter Flying and Ground Handling Qualities: General Requirements for, MIL-H-8501A, Sept 1961.
2. McRuer, D. T. and Krendel, E. S., "Mathematical Models of Human Pilot Behavior," AGARD-AG-188, January 1974.
3. Anon, ADS Handling Qualities Rotary Wing, United States Army Aviation Systems Command, ADS 33, Dec. 1985.
4. Hoh, Roger H., "Investigation of Outside Visual Cues Required for Hover," AIAA Paper No. 85-1808-CP, August 1985.
5. McDonnell, John D., Pilot Rating Techniques for the Estimation and Evaluation of Handling Qualities, AFDL-TR-68-76, Dec. 1968.
6. Morgan, J. M., Airborne Simulation at the National Aeronautical Establishment of Canada, AGARD Flight Mechanics Panel CP Sept. 1985.
7. Hoh, R. H., D. G. Mitchell, and I. L. Ashkenas, Background Information and User's Guide for Proposed Handling Qualities Requirements for Military Rotorcraft, TR-1194-3, 20 Dec. 1985.
8. Hoh, Roger H., and David G. Mitchell, Proposed Revisions to MIL-F-833000, V/STOL Flying Qualities Specification, NADC-82146-60, January 1986
9. Snedecor, G. H., and W. G. Cochran, Statistical Methods, The Iowa State University Press, Ames Ioway, 1967.
10. Military Specification, Flying Qualities of Piloted Airplanes, MIL-F-8785C, Nov. 1980.
11. Cornsweet, Tom N., Visual Perception, Academic Press, New York, 1970.
12. Van Nes, F. L., and M. A. Bouman, "The Effects of Wavelength and Luminace on Visual Modulation Transfer," Exerpta Medica, Intern. Cong. Ser. No. 125. "Performance of the Eye at Low Luminance," Proc. of the Sympisium, Delft, 1965.