Adequate structural mode stability may limit system ride smoothing performance.

Control system nonlinearities during severe turbulence can cause excessive structural loading and reduced stability. Based on nonlinear analyses, design criteria must be defined to prevent this possibility.

This study assumed that the flap rear segment can be driven in retracted and extended positions. Potential problems associated with mechanizing a high response, aft segment full-span double-slotted flap should be considered. Related areas for study include redundancy, hydraulic power, and flap segment requirements.

Although the primary objective of the RCS is to provide ride smoothing, handling qualities and maneuvering requirements must be satisfied within the airplane operational flight envelope. Compatibility of these two functions must be thoroughly analyzed.

Conclusion

Keeping in mind the potential problems noted, this brief study indicates that a low wing-loading STOL aircraft with a ride control system provides satisfactory ride qualities and competitive high-speed performance. Further studies and flight tests should be conducted to analyze potential problems in depth and to obtain additional confidence in the concept.

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Application of the Head-Up Display (HUD) to a Commercial Jet Transport

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Previous work with HUD is extended by solving problems of installation in a commercial jet transport, and by demonstrating a high order of accuracy in manual control. Spatial aspects of the symbol format are organized to accord with principles promoting a balanced flow of information from the pilot's superimposed visual fields. Alternate installations are compared in DC-9 flight tests, an overhead mounting being found less prone to glare effects. Temporal aspects of the format are optimized by determining empirical relationships between gains and performance measures, for one test pilot, and conditions are chosen which enable subsequent users consistently to demonstrate equivalence between manual and automatic methods of flight control. Consequently, a new basis is suggested for evaluating an all-weather approach system.

Introduction

THE original purpose of the Head-Up Display (HUD) was simply to supply information during visual flight without reducing the ability to see the outside world. But it was found, in the course of development for military airplanes, that the system was used with greater accuracy than a conventional flight instrument system.[1] The level of tracking accuracy was sufficient to allow comparison with an automatic flight control system, as indicated by Morrall,[2] and this suggested the possibility of an alternate method of all-weather approach and landing. Preliminary investigation with an experimental display installation, a small group of pilots, and in one type of commercial jet transport showed that full manual landings could be made in simulated category III conditions.[3] These results were promising, but needed to be confirmed; and it was clearly necessary to provide a more generally acceptable installation.

Although there is little difficulty in the military field, it is an immediate problem in commercial application to find room for the display equipment. A reflecting collimator has to be installed without affecting the view through the windshield, and without disturbing or obscuring the panel instruments. In the preliminary work it was sufficient to strap the display unit directly to the glareshield, ignoring interference with the forward view. But a more satisfactory method is now needed for production purposes.

Confirmation of the previously observed level of tracking accuracy, for a larger group of pilots, implies an optimum presentation, in which all aspects of the display are matched

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to human capabilities. The spatial aspect, or visible form of presentation, has already been studied in this context, according to a rationale which will be given immediately. But less attention has been given to the temporal aspect of presentation in HUD, as mediated by control gains for the command symbol, which were previously chosen by ad hoc methods. A more thorough investigation of this matter is now made, thus securing similarity in the treatment of control information in manual and automatic flight, and removing a possible source of dissimilar performance. Other characteristics of manual HUD flight are considered, as a basis for comparison with automatic control, and for judging an all-weather system.

Principles of Organization of Symbol Format

The most immediately obvious principle to be considered in head-up presentation is of conformity between display and background, in the sense of allowing the superimposed fields to be understood by similar rules. This leads to a reduction in the interpretative or mental workload, which is the counterpart of the reduction in physiological workload achieved by locating display and forward view in the same position. Conformity has been found to benefit tracking performance,[1] but it cannot be used generally without reservation. For example, it does not entirely justify a runway symbol, which is subject to errors and optical limitations.[4] And a pictorial, or "real-world" display of height or speed is inefficient because information of this type is not plentiful in the pilot's forward view. It follows that conformity does not require one-to-one correspondence between display and background, but simply that corresponding features be found within a common framework, or coordinate system.

An application of the principle is in showing a heading change as a displacement in Earth axes, instead of the usual presentation in aircraft axes, the change to a conformable arrangement amounting to the elimination of one set of axes. A more obvious application is in using a fixed symbol to represent the longitudinal axis of the aircraft.

Conformity also leads to a reduction in workload. This is believed to occur because skills already learnt by the pilot in visual flight can be applied in using HUD.[1] And conformity allows free movement between fields, thus eliminating the transition.[5]

The need for a simple format is fundamental in a display interrupting the pilot's main sensory link with his environment. Ornate symbols clutter the background and may take longer to interpret. A large number of symbols is undesirable for similar reasons. A format consisting of a few symbols, having distinct yet simple forms, allows both the (conformable) display and external world to be observed efficiently.[1,5]

Harmony is desirable in the relation of parts of the format to the whole. No component should achieve prominence above its proper value, whether through attracting too much attention or through impeding the flow. And just as a control (by conformity) is needed to promote transfer between superimposed fields, a balance is needed in governing the flow of information from parts of the display field itself. This is influenced by several factors.

Since time is needed to alter the line of regard, the accessibility of a symbol depends on its angular distance from datum. It also depends on the area occupied by the symbol, a larger symbol being seen whenever the line of regard occupies one of a larger set of possible viewing directions. And a moving symbol becomes more prominent as its angular velocity increases. But these factors are not infinitely variable. The position of a symbol may to some extent be determined by conventional usage in the flight instrument panel, or it may be desirable to use particular dispositions to promote a scan pattern,[5] and the velocity of a symbol may depend very much on information rate. On the other hand, area is more generally available as a control.

Symbols occupying the same part of the format tend to interfere with each other. This can be avoided by confining each symbol, or component, within its own zone. The holistic principle of balanced transfer may then be used to give position and area to the zone.

Zoning is especially important for symbols having a pictorial relation with the outside world, because they tend to move freely through the format. In the case of a command symbol, zoning is not difficult since no absolute quantity need be involved. It can also be achieved for the artificial horizon, by scaling down its movements in elevation, and this seems to be acceptable because the visible horizon is often far removed from the best display position[5] through dip, visibility, and terrain variations. Zoning cannot be achieved for a one-to-one runway symbol.

As a general rule, it is desirable to organize the display system on the principle that the user should not be able to gain false information. Now the validity of a symbol depends on the integrity of the data source, but it may also depend on the way the symbol is generated. In the event of any data source failure, it is a simple matter to blank off a symbol, but display generation errors require careful consideration because symbols vary in their power to resist them.[4] Abstract symbols are better in this respect, but if pictorial symbols are used, an incorrectly drawn shape should be capable of removal, as giving a false clue to the external world. (This removal, of course, is to be distinguished from a natural excursion from the format due to change of aircraft attitude.)

Form and Characteristics of Symbols

A format based on these principles is shown in Fig. 1. At the center is a fixed aircraft symbol in the form of a circle with stub wings. From this an artificial horizon is displaced to show angles of bank and elevation (the latter at reduced scale), and this symbol is in the form of a bar from which the center is removed, to avoid interference. The flight director (or command) symbol has the form of a stack of lines, always parallel with the horizon, and falling within a triangular envelope. Lateral and vertical distortions of the envelope, from aircraft datum, are used to show azimuth and elevation commands, respectively. This symbol is given the greatest weight, and occupies the largest, central zone. It is essentially a "fly-to," Earth axes, dot and circle arrangement, with an extended form added to avoid effects of hypnosis and interference. In conjunction with the horizon, which shows the nature of a command being satisfied, the director is both "pursuit" and "compensatory" in type.

To this basic display (essentially unchanged in ten years of flight usage) peripheral components are added to show speed error, height, and raw ILS displacements. The speed component is a simple three-dot scale and pointer, showing slow and fast (S, F) departures from a given speed, or angle of attack. It can be placed in the conventional position at the left of the central zone, but it is shown in Fig. 1 at the top of the format, to indicate a capability for slewing during a crosswind approach. The height component is a digital readout of radar altitude which is changed at a given sampling interval, such as every 20 ft, and can thus also be used as a source of

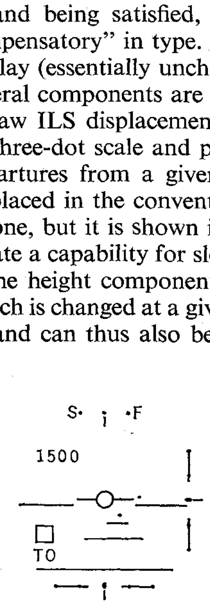

Fig. 1 Symbol format.

height rate information. It is placed to the left of center, to secure minimum scanning distances between aircraft datum and digits representing units and tens, a new arrangement which becomes significant during flare. The format is completed by five-dot scales showing ILS displacements. These components have conventional positions, although the glide slope scale can be placed at either side for crosswind slewing.

The basic format can be modified temporarily by means of discrete messages, such as T-O (takeoff), and a square intermittent warning symbol in the lower left quadrant. It is also possible to monitor the approach by adding a "gate," or the computed tolerance at a given time, and this can be represented by the distance between bars superimposed on each ILS scale. Both gates and scales are conveniently removed at heights less than about 200 ft.

Installation

The symbol format is to be presented at infinity in the direction of the forward view from eye datum. For this purpose a partial reflector needs to be placed in the forward sight line, and an optical collimator directed towards it. Since the collimator barrel is solid, and of dimensions which cannot easily be reduced, it is liable to obscure either windshield or instrument panel.

Barrel dimensions are determined by the diameter and focal length of the collimating lens system, and by the length of a cathode ray tube used to generate the symbol format in the focal plane. The lens diameter determines the head freedom, or the range of viewpoints from which a given symbol can be seen, and this usually needs to be about 4 in. With an $f/1$ system, the focal length is then also 4 in. while the tube length cannot be (even with the latest type of high-voltage connection) much less than 7 in., when providing for operation at high brightness levels. The barrel is thus about 12 in. long, and a little more than 4 in. in diameter.

It would obviously be unobtrusive if the collimator could be stowed at some distance from the eye position. But this would reduce the (instantaneous) optical field, which depends inversely on viewing distance. Only a small region of the focal plane would then be visible from a given eye position, thus restricting the number of symbols (of given line width), and their range of movement. For a format of adequate content, it is impracticable to reduce the instantaneous field to much less than 10°; i.e. the viewing distance should not exceed about 24 in. in the case of a 4-in. collimator. (Alternately, a remote imaging system might be used, but little success has yet been achieved by this method, partly because of vibration problems arising in the extended optical train.)

One method of meeting these conditions of collimator orientation, volume, and viewing distance, without obscuration and without appreciably altering an existing instrument layout or wheel configuration, is shown in Fig. 2. This is a glareshield installation of an integral unit, the reflector being attached to the collimator barrel. It is a simple modification of the conventional (folded) gunsight arrangement with the whole unit turned through some 45°, about a longitudinal axis, to remove the barrel from the region of the chief flight instruments. The instantaneous field is 10.25°, and the installation penalty is in needing to move caution and warning indicators.

Another method of solving the installation problem is by separating the collimator from the reflector, and mounting it (as a straight-through system) above the pilot's head, Fig. 3. A possible disadvantage in this case is that relative movement may occur between collimator and reflector (although this will only be serious for rotations about lateral or vertical axes). In this arrangement the viewing distance is increased to 25 in., for the barrel to clear the windshield aperture, and the instantaneous field is a little over 9°.

Flight Evaluation of Equipment and Installation

Overhead and glareshield mountings of 4-in. HUD systems were installed at the Captain's and First Officer's stations in a DC-9-20 airplane, as shown in Figs. 3 and 2, respectively. It is seen that only reflectors and controls were operationally significant. The top edge of each reflector was curved to avoid the suggestion of a preferred level in the external world. A small panel with brightness override and centering controls, for each system, was placed near the base of the reflector. The Captain's reflector could be stowed by folding downwards.

Prior to flight evaluation, the system was calibrated to establish reference positions, polarities, and scale factors. In the process, it was found impracticable to boresight the format except by complicating the shift controls and support for the movable reflector, thus ruling out a simple yet efficient presentation of flight path angle. A capability for trimming the horizon bar was found to be a potential hazard, and was eliminated. The elevation scale factor for the artificial horizon was 12.0. The speed display had a mid value of 12° of angle of attack, and a swing of $\pm 8°$. The radar height read-out was set to change at 20-ft intervals, and calibration was carried out during slow changes of altitude in real flight.

Fig. 2 Glareshield installation of integral reflecting collimator in DC-9.

Fig. 3 Overhead installation of collimator with glareshield mounted reflector in DC-9.

Another part of the procedure was to check occulation, failure warning, and the selection of symbols according to flight mode (as determined by the flight director mode selector).

Equipment

The display equipment included collimator, cathode ray tube, and circuits generating the format waveform. These were judged for their effects on the transfer of information, chiefly by the subjective evidence of two experimental test pilots (S1, S2). The collimator was considered in terms of sensible aberrations. Parallax, observed by head movement during stable flight, was only evident at the edge of the field. Distortion, observed during ground tests, was only seen as a slight curl in the ends of the horizon bar. Chromatic aberration was not observed, for a range of brightness and against a variety of backgrounds. And the cumulative effect of residual aberrations was small enough to allow continuous use without eyestrain for periods up to 3½ hr. On the basis of these observations, the quality of optical design was entirely satisfactory.

The optical system was also evaluated in terms of its design parameters. An instantaneous field of 9°, at the Captain's station, was found sufficient for seeing all that was needed of the format of Fig. 1 at any one moment. A head freedom of 4 in. (nominal) was entirely acceptable for the purpose of regaining the same eye position after making a body movement, as in setting the compass. The total field, covering all regions of the cathode ray tube visible by moving the head, was about 25°; this allowed the format to be slewed by about 8°, thus providing against crosswinds of some 18 knots. Many users, however, found it unnecessary to slew the format, preferring to use an offset display, and thus avoid crosswind limitations. With this reservation, it was concluded that suitable parameters had been chosen.

Significant characteristics of the cathode ray tube were brightness, color, and line width. There was an even distribution of brightness, and the format was visible against snow-capped, sunlit mountains when using a 15–20% neutral reflecting surface. This was achieved with a nominal apparent brightness of 2450 ft lamberts, at 80% transmission. It was also possible, though with less flexibility of operation, to use uncoated reflectors under most daylight conditions. Throughout the operational range, brightness was held automatically at a suitable differential with respect to the background, though the control was rather too coarse for use by night. Otherwise, brightness characteristics were entirely satisfactory.

Color was also very suitable, the uniform green (5500 Å) giving coherence to the format, so that no symbols were confused with the background (even at night), while the format design allowed each symbol to be distinguished from its fellows. And there were no effects of chromatic relief, or apparent change of object distance with color. Line width was sufficiently small for all of the format to be resolved, the smallest detail subtending approximately 1 mrad. This was true at all levels of brightness, at least for the early life of the tube. It was concluded that satisfactory performance could be achieved in a 7-in. model.

The waveform generator was assessed for its ability to draw the symbol format, in terms of errors of form or position, and their changes with time. There were few complaints of form errors but it was found that quite a large matrix, of 5 × 7 elements, was needed in writing numerals without ambiguity. The only serious position error occurred in the First Officer's equipment, as a drift in the flight director datum. Noise effects were at first troublesome (except that transients were useful in denoting changes of flight mode), but these effects were largely reduced by improved grounding, and by rate limiting, the latter technique being especially useful with transients arising during an approach over a parked aircraft. It was also necessary to improve the quality of the bank-resolving sine-cosine potentiometer (used to avoid electronic multipliers) which could cause massive (though occasional) noise effects. With these exceptions, an acceptable standard of waveform generation was available.

Since the display format was very much the same as in previous work, it needed no very extensive investigation. Apart from minor dimensional changes, the main differences were in providing a variable height interval, and in adding raw ILS and warning information. The digital height readout, though rather too small, was easily understood, convenient, and free of problems during change of digits. It was recommended that the sampling interval be increased to 50 ft at heights greater than 1000 ft, and decreased to 10 ft at heights less than 200 ft. There were very few complaints about the lack of a separate display of rate of change of height. The ILS scales were also satisfactory and, except at low altitude, they were useful in monitoring the approach during conditions of shear, turbulence, and beam bending. This led to the suggestion of adding performance gates (S1), which might be achieved by the method shown in Fig. 1. The master warning symbol was found to be a satisfactory means of attracting attention, yet without rendering useless the rest of the display. These changes to the format had been made without introducing problems of identification, interference or excessive clutter, and were evidently satisfactory.

Installation

Comparison of the two installations showed similarities in most features of the optical systems. Mechanical features were also quite similar. Vibrations, noticeable chiefly at flap buffet, were easily suppressed in each installation by bracing the glareshield for the weight of added equipment, and there was no mechanical noise penalty in separating reflector and collimator. Moreover, neither system caused appreciable obscuration of the forward view, though instruments for mode and advisory information were hidden by the equipment mounted in the glareshield. In fact, glareshield installation almost necessarily entails rearrangement in the panel area of a commercial airplane, whereas only secondary items, such as map light and ventilator, may need to be moved for overhead installation.

Body clearances were generally sufficient, though the First Officer's hand clearance was not acceptable, and the Captain's head clearance was insufficient for changing seat position when leaning forward. The reflector was satisfactory at each station, except that a few pilots experienced a sense of restriction. An extended reflector was tried in an attempt to improve the situation, but this was abandoned because of difficulties in mounting, surface coating, optical quality, and reflections from cockpit lights. The general problem of cockpit reflections did not arise with either of the smaller reflectors, but a serious difficulty was experienced through sunlight entering directly into the glareshield collimator. This proved to be the main factor weighing judgment in favor of the overhead installation.

Flight and Simulator Investigation of Manual Performance

Basis for Gain Adjustment

It has already been noted that not all symbols need move in one-to-one correspondence with the external world. Indeed, a command symbol would then become unduly prominent, as flight tests have consistently shown, and this is perhaps due to the constrictive effect of a limited display field. The outer loop gains, affecting heading and elevation displacements, should therefore be less than unity (as an angular ratio) and other gains should be reduced in proportion. The basis for choosing an over-all scaling factor is thus empirical, being bounded by subjective effects of velocity prominence and, at the other extreme, of information loss.

Within this over-all limitation, gains might be adjusted for best tracking performance by theoretical methods based on a mathematical model of the human pilot, but this would not guarantee optimum gains because of uncertainty in the choice of model, especially in the head-up mode. Moreover, weight would not necessarily be given to the pilot's estimates of controllability and workload, which can hardly be ignored without some effect on motivation and, perhaps, performance. For these reasons it was decided to adjust gains by empirical methods, giving weight to both tracking error and pilot rating.

Command Information and Performance Measurement

The overhead installation of HUD was used for the experimental program in conjunction with a steering command generator and means for integrating the unsigned value of the pilot's tracking error. Azimuthal steering commands comprised the usual mixture of glide path (localizer), heading error, and bank attitude signals, but with the addition of an attitude rate signal. By varying the several contributions, heading, bank rate, heading-to-bank, and localizer gains were adjusted. A similar arrangement was used in the elevation channel for adjusting pitch attitude, attitude rate, and glide slope gains. The error integrator, which accepted the same command signals as HUD and thus returned a low score for a well-executed task, was calibrated in terms of fixed angular glide path errors giving equivalent error scores, in azimuth and elevation.

The experimental assembly was designed to be transferred in toto (except for a change in collimator mounting) between the DC-9-20 and a simulation of the test vehicle. The basic display format of Fig. 1 was seen against a dark ground in each case, and this was achieved in real flight by mounting polaroid screens over the windshield panel and in goggles worn by the pilot. After completing the gain adjustment program, the format was also used with uncrossed polars, as shown for a landing approach in Fig. 4.

Flight and Simulator Programs

The first phase was conducted (except for a subsidiary gain) with one subject (S1), an experimental test pilot with 3000 hr flight time. His task was to fly groups of instrument approaches, with the best accuracy possible in the prevailing environmental conditions, along a path intended to coincide with that defined by a conventional Instrument Landing System. In each group, one gain was varied between approaches, all other gains being held constant at near-optimum values. The subject knew which gain was the experimental variable, but did not know the (random) order in which values were taken. Tracking errors were integrated for a measured time between heights of 1200 ft and 250 ft, approximately, during which gains could reasonably be held constant. Subjective (pilot rating) measures were also recorded.

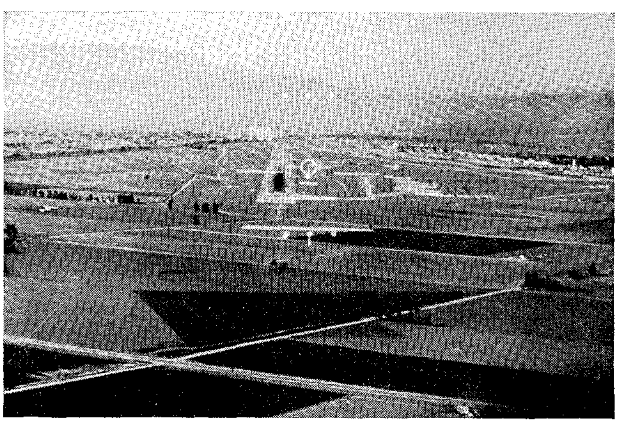

Fig. 4 HUD in landing approach.

All runs in any one group of about seven approaches were flown at the same airport, except for two individual runs. Autothrottles were engaged, and most approaches were made in smooth air. Two or three groups were completed in a flight lasting between 3 and 4 hr. There were no practice or replicated runs because learning effects were negligible for the format in use. At the conclusion of the flight program, a similar investigation was conducted in the simulator with the same subject. For this, the simulated ILS was given representative characteristics of beam noise (0.14° rms and flat to 30 cycles in elevation, 0.056° rms and flat to 1.5 cycles in azimuth). Autothrottles were not used, resulting in some increase in workload, and practice runs were included as a substitute for the effect of transit to the real flight test location.

For the second phase, gains were selected from the experimental results, as will be described, for use by a greater number of subjects, S3-41, all experienced pilots. The procedure with most subjects (S6-41) was to start using the display system on the downwind leg of the first approach, which was completed in smooth, visual, flight conditions with autothrottles engaged and after almost no practice. Then two approaches were made with crossed polars, to a height of 100 ft. On the second of these a landing was attempted, after forward visibility had been restored, and on one of them the display was deliberately misaligned. A less definite procedure was followed with other subjects (S3-5), who were more familiar with the test vehicle, but tracking errors were recorded in all cases. These were used to determine the performance level for a typical manual approach with HUD.

Gain Selection and Manual Performance Levels

Experimental results for this particular gain survey can be arranged in three classes.

a) Yielding relations between (unseen) gain and performance measures with prominent but different trends, tracking error decreasing asymptotically to a minimum at high gains (for the channel affected by the gain), and pilot rating decreasing to a local minimum at an intermediate gain (best liked value). Curves for heading and pitch attitude gains were in this class, as shown for the latter in Fig 5.

b) Showing less prominent but similar trends, with minimum tracking error and best pilot rating at approximately the same intermediate gain value. Results for pitch and bank rate gain ratios were in this class.

c) Showing less prominent and dissimilar trends, with tracking error decreasing but pilot rating constant or increasing slightly at high gains. Results for glide slope and localizer gain ratios were in this class. Results for heading-to-bank ratio showed slight and indefinite trends, but could possibly be included in this class.

In general, results in real flight were somewhat less consistent, and tracking errors in six out of seven cases were higher than in simulated flight, perhaps through effects of turbulence. But where trends were observed in both modes of flight, they were similar (in spite of differences in throttle procedure), thus removing a possible difficulty in choosing the best gains. As regards the two measures of performance, the choice was less straightforward. In class a, where different minima were found for each measure, it was decided to give greater weight to pilot rating, while accepting a small performance penalty. In class b, slightly suboptimal gains were chosen, because subsequent users were expected to be unfamiliar with this class of (rate) information. Other small reductions were made for S6-41, who were expected to be pre-disposed towards the smaller gains typical of conventional

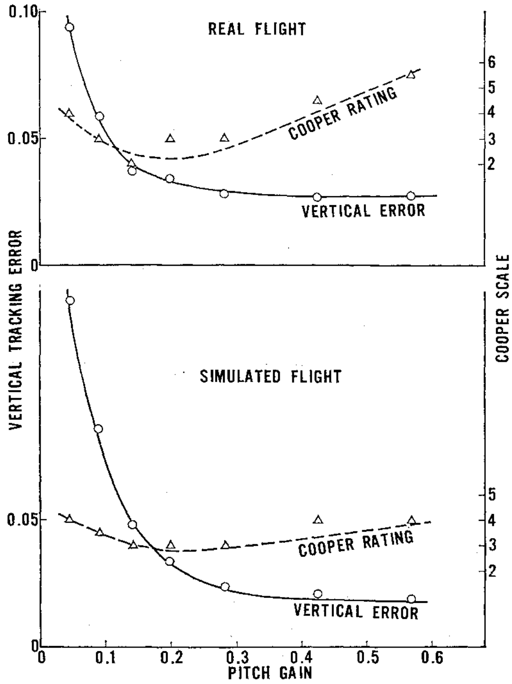

Fig. 5 Variation of tracking error and Cooper rating with pitch attitude gain for single subject.

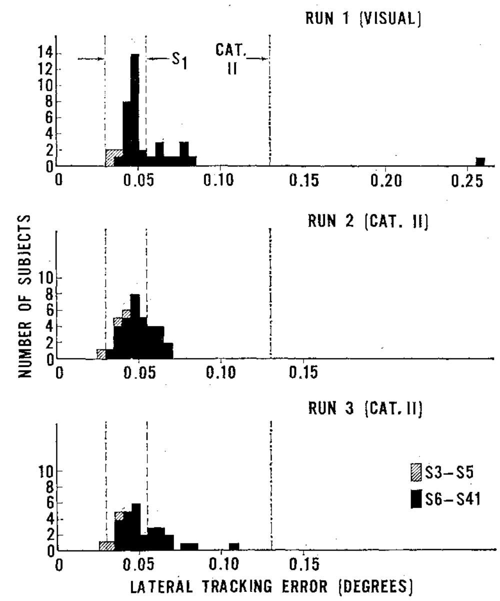

Fig. 6 Tracking performance of subsequent users.

displays. Table 1 gives the final values selected to give good conditions and error scores, and includes a range of glide slope gains used at lower altitude in some cases (necessitating different calibration).

The histograms of Fig. 6 show lateral tracking errors (which were greater than vertical errors) for the three approaches made by S3-41, with the selected gains. Scores for S3-5, shown hatched, were generally smaller than for S6-41, who used gains further removed from optimum. Of all scores, a large fraction (always more than 64%) fell within or below the limits for S1, represented by the dotted vertical lines. In other words, there was a rapid approach to the level of an experienced user. And except for one subject on his first approach, all scores were less than the mean limiting performance, derived from the 95% probability criterion, for category II landing weather minima, which is represented by the chain dotted vertical line. Further, all subjects made at least one (touch-and-go) landing on the third run, some at night.

Performance in manual flight with the optimized display system was thus quite uniform over subjects and compared very favorably with the standard required for automatic operation in poor visibility. This is further illustrated, though with less certainty, by finding the standard deviation of the height error at a height of 100 ft, a similar statistic being available for automatic flight. On the assumption that each run was part of a stationary random process, the one-sigma value for typical HUD manual flight would be 2.1 ft: for automatic flight in a similar airplane, with similar ILS guidance facilities but in more general conditions of turbulence, it was previously found to be 3.3 ft. After allowing for different turbulence levels, these values may be considered broadly equivalent, especially in view of the earlier success in manual landings.[3]

Basis for Choice of All-Weather System

The results suggest that it may no longer be possible to justify an all-weather flight system on the supposedly better accuracy of automatic control. An approach may be made to a height of 100 ft by either automatic or manual methods with acceptable, and probably equivalent accuracy. It may be taken beyond this point to touchdown, as in the visual flight conditions of the present work, or in the "blind" conditions of previous work. The choice between human and automatic operation, in this type of airplane, should therefore rest on other grounds.

An obvious consideration is reliability, and it is clear that a manual system would need the same scrutiny as an automatic system in respect of the frequency, and the consequence of failures. Fortunately, there is a reasonable chance of meeting this challenge because of the relative simplicity of a manual system, and because of protective techniques possible in the symbol generating circuits and in the format itself.

Another basis for comparison is pilot workload, particularly in the presence of high or discontinuous information rates. It has to be shown that the pilot is not likely to make a serious mistake. There may be insufficient evidence to judge this possibility at the present time, for either system, but it is interesting to note that there were no disorienting effects with HUD due to introducing the forward view during the last ten seconds of flight. This quite critical test gave the same result when the superimposed display was deliberately misaligned, and is attributed to being able to move freely between the outside world and a conformable, but not identical display. There was evidently a very reasonable division of attention between the superimposed fields (each contributing to the total load), and this was confirmed by reports of good visual pick-up in the outside world, and of being able to use displayed height information during a visually performed flare maneuver. Further evidence of low workload can be found in the short time, of the order of 5 min., needed for subsequent

Table 1 Gains selected for good operating conditions and performance

Subject	Heading	Bank rate	Pitch	Pitch rate	Heading to bank	Glide slope	Localizer
S3-5	0.088	0.33	0.141	0.33	1.3	12.9 to 31	33.6
S6-41	0.079	0.33	0.127	0.33	1.3	10.3 to 31	25.6

users to approach and maintain the performance level of an experienced subject. These findings, which confirmed previous results for learning[1] and concurrent acquisition,[5] showed workload to be not unreasonably greater than in automatic flight.

Perhaps the most important area for comparison is the total information coverage. For although a perfect automatic system may safely accomplish landings without the pilot needing to observe the external world, it does nothing to help him observe externally, or to assist him in taking control, should the need arise through environmental conditions of excessive turbulence, wind shear, or beam bend. Similarly, the pilot may be left unprepared, at the moment of touchdown, for a roll-out which has to be completed without ILS guidance (for which the performance is not yet defined). And, of course, a control system has no knowledge of traffic intruding on its airspace. These difficulties can be avoided since they arise through information discontinuities, of the order of 3 sec, which are due to changes (during the transition) in focus, line of regard, and method of visual interpretation. They are eliminated in the manual-HUD approach,[1] as are effects of space myopia, or short-sightedness induced by an empty field, which delay the sighting and comprehension of external events. An uninterrupted flow from a complex of control, monitor, and external information appears to be highly significant during takeover, whether in the approach or at touchdown.

The choice of an all-weather system may amount ultimately to a decision between doing very little work, with incomplete information, at some risk of losing flying skill; and doing more work, with comprehensive information, at no cost in skill (Table 2). There is, of course, a new emphasis reflected in this comparison, which results from a control accuracy, and a freedom from disorientation, due to temporal and spatial improvements in methods of displaying information. More general aspects of HUD include use as a primary flight instrument system, as a monitor and reversionary facility, as a visual approach aid, and as a means for improving safety, but these are beyond the scope of the present discussion.

References

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Table 2 Comparison of HUD manual and automatic operation

Operation	Accuracy	Workload	Information	Disorientation probability	Skill maintainability
HUD Manual	Cat. II or III	Moderate	Comprehensive	Small	Good
Automatic	Cat. II or III	Low	Incomplete	Small	Poor