Applications of Head-Up Displays in Commercial Transport Aircraft

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Development of the head-up display (HUD) is traced from its earliest form, in which two angle-of-depression sights indicate to the pilot the desired and the actual direction of descent of his aircraft, to the most recent design that uses feedback compensated control systems, a digital computer, and the latest display technologies. A brief analysis of the effect of HUD on the control of aircraft dynamics is included. The control law concept employed by the DC-9 Super 80 HUD is summarized, and the hardware and software for this system, including the pilot display unit, are described. In addition, newly developed HUD cruise modes are described.

Nomenclature

A_n	= aircraft normal acceleration, ft/s^2
h	= aircraft altitude, ft
$\dot{h}$	= aircraft vertical speed, ft/s
$\dot{h}_\delta$	= vertical speed on selected glideslope, ft/s
K_{alt}	= lead variable gain
K_{A_n}	= normal acceleration lead gain
$K_{\dot{h}}$	= vertical speed gain
K_v	= $\delta\gamma$ control law constant with constant V
$K_{\delta\gamma}$	= fraction of γ in $\delta\gamma$ control law
K_θ	= pitch lead gain
$K_{\dot{\theta}}$	= pitch rate lead gain
s	= Laplace operator
V	= aircraft measured horizontal speed, ft/s
γ	= aircraft vertical plane velocity vector, deg
δ	= selected glideslope depression angle, deg
δ_e	= elevator deflection, deg
η_a	= depression angle of aimpoint, deg
η_{ld}	= aircraft motion computed lead, deg
η_{se}	= control error, deg
η_{sym}	= depression angle of HUD guidance symbol, deg
θ	= aircraft pitch angle, deg
$\dot{\theta}$	= aircraft pitch rate, deg/s
ω_{A_n}	= normal acceleration filter frequency, rad/s
$\omega_{\dot{h}}$	= vertical speed washout rate, rad/s
ω_θ	= pitch washout rate, rad/s
$\omega_{\dot{\theta}}$	= pitch rate filter fequency, rad/s

Introduction

A COMMERCIAL transport pilot encounters his most demanding tasks during approach and landing. With or without autoland, he must be able to assess the actual position of his aircraft relative to the desired approach path and to determine the immediate corrective action that might be needed. The difficulty of his decisions is frequently compounded by adverse factors such as variable visibility or ceiling, nighttime, wind shear, and illusions caused by runway lighting, area lighting, runway slope, and runway dimensions. In the worst case, the pilot must decide if he can safely continue an approach or abandon it. A suitable head-up display (HUD) design will help the pilot to overcome these factors by simplifying his tasks of decision making, control, and management, and relieving him of the need to take his eyes from the view ahead to refer to his panel instruments.

The transition from head-down to head-up is a potential source of trouble. The pilot, who is dependent upon panel instruments either to monitor the autopilot or to control the aircraft as he proceeds down the approach path, wishes to see the runway at the earliest possible moment as he descends below the clouds. Studies have been made to determine the time required (from the time he looks up from the instrument panel) for him to evaluate the runway visual environment adequately enough to achieve precise path control or to recognize path deviation when monitoring the autopilot. According to Haines,[1] the mean time required ranges from 2 to 4.6 s for ceilings under 380 ft. If the pilot tries to fly head-up too soon, or at a critical time during an approach, his aircraft could deviate beyond his ability to recover before he becomes aware of it (Fig. 1). This is what occurred when the 727 aircraft approaching JFK Airport encountered a severe wind shear at the time the pilot was trying to transition to head-up, ending in the crash ½ mile short of the runway. An adequate HUD removes the necessity of transitioning during the approach. During a visual approach the pilot can keep his attention on all available visual cues (including possible dangers) in the landing area and still have available all information necessary to complete a safe approach. During an instrument approach, all guidance cues are available head-up whether or not any ground cues are visible.

The continuous advancing state of the art has improved the HUD with a larger field of view, more distinct images, and more easily followed symbology. These improvements have been made possible by advancements in HUD optic design, the use of the cathode-ray tube (CRT), the digital computer, and more sophisticated control laws. The commercial transport HUD system that is certified for the DC-9 Super 80 benefits from these improvements.

History

As early as the mid-1950s, it was recognized that the aimsight used on military aircraft could be adapted to a HUD

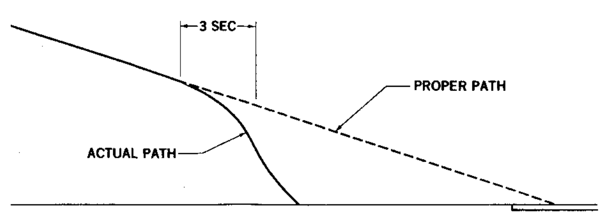

Fig. 1 Effect of transitioning in wind shear.

Submitted Nov. 10, 1981; presented as Paper 81-2300 at the AIAA/IEEE 4th Digital Avionics Systems Conference, St. Louis, Mo., Nov. 17-19, 1981; revision received Oct. 18, 1982.

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for providing the pilot with landing approach path guidance. The first approach path HUD, developed by Lane and Cumming[2] for use during a visual approach, consisted of two displays. One indicated the desired descent angle; the other, the aircraft's actual descent angle or velocity vector (Fig. 2). By maneuvering his aircraft so that the velocity vector display lined up with the desired descent angle, and the desired descent angle lined up with the runway touchdown zone, the pilot was directed to fly down the desired approach path. Also in the 1950s, the advantages of a single display over the two displays led Gold to combine the two electronically[3] (Fig. 3). Closely following development of the first visual HUDs, a flight-director-type HUD was developed in the early 1960s for limited-visibility approaches into instrumented runways. It basically applied the head-down flight director commands, derived from instrument landing system (ILS) signals, to a head-up display.

More recently, HUD technology has advanced to the point where autopilot design techniques are used in the development of HUD control laws. Such techniques effectively eliminate the velocity vector and the errors that result from it in wind conditions. How errors are caused by wind when an airmass derived velocity vector is used to drive the HUD symbology was described in an earlier paper.[4] In wind, the airmass in which the aircraft is moving is itself moving relative to the ground, causing the actual speed of the aircraft relative to the ground to be the vector sum of measured airspeed and wind speed.

In a thunderstorm-type wind shear, where an aircraft may fly into a decreasing headwind and a downdraft burst, the velocity vector wind error can be potentially serious, particularly when the velocity vector is derived from measured angle of attack. An increased downdraft causes the relative wind angle (measured by the angle of attack) to decrease. This causes the velocity vector computed descent angle to decrease, deflecting the velocity vector HUD symbol upward, and therefore causing the pilot to direct the aircraft to descend more steeply to keep the symbol at the same depression angle. The pilot is actually commanded to fly down with the angle-of-attack velocity vector when, under these conditions, he should be commanded to fly up. At the time this referenced paper[4] was written, the angle-of-attack velocity vector was popular, particularly in Europe.

The velocity vector may be derived from the ratio of barometric altitude rate to airspeed. It has been shown that the measured barometric rate closely indicates the true vertical speed, but the airspeed differs from the ground speed by the amount of wind velocity. Therefore, in a headwind, which causes the airspeed to be greater than the ground speed, the airspeed derived velocity vector symbol will indicate a descent angle that is shallower than true. This will cause the pilot to descend more steeply to keep the velocity vector symbol on his aimpoint, thereby deviating below his desired descent angle.

The guidance error caused by an airmass measured velocity vector in previous HUDs has been tolerated, or else an inertial velocity vector that requires an inertial navigation system has been used. The application of a feedback compensated control system to HUD guidance eliminates the need for a velocity vector. The feedback compensated control system allows adjustment flexibility to achieve the desired performance. The compensated control HUD in the DC-9 Super 80 is such a system, and is referenced to the desired descent angle. The lead, or rate damping, that is applied to the desired descent angle includes only signals that have zero steady state. To achieve rate damping, other HUDs produced in Europe or the U.S. are dependent upon a measured velocity vector angle, which may contain a steady-state error.

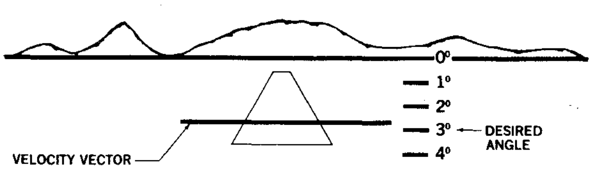

Fig. 2 Two-display HUD.

Compensated Control Law

Basically, the new HUD control law, called compensated control, adds lead parameters to the desired descent angle aimsight of the Lane and Cumming HUD. The lead parameters used in the DC-9-80 HUD are washed-out pitch, pitch rate, washed-out vertical speed, and normal acceleration. A feedback compensated control system is optimized by adjusting the gain and time constants of the feedback parameters. Optimization is first performed with the mathematics of control system synthesis and is later refined acording to pilot opinion during simulator and flight testing to achieve vertical guidance that is accurate, smooth, and easily flyable.

A block diagram of the closed-loop compensated control system is shown in Fig. 4. To track the glidepath, the pilot observes the depression angle of the aircraft symbol η_{sym} relative to the depression angle of the aimpoint η_a. His vertical control task is to operate the elevators δ_e to keep the aircraft symbol superimposed on the aimpoint, i.e., to hold η_{se} at zero. (If the aimpoint is not visible due to foul weather, and the airfield has an ILS, the direction of the aimpoint is indicated by an aimpoint symbol in the HUD.) The dynamics of the aircraft symbol η_{sym} depend upon the lead that is computed from the measured aircraft motion parameters η_{ld}. The steady-state position of the aircraft symbol is the selected approach path depression angle δ. Figure 5 shows the geometrical relationships of these angles.

Consider a situation where the aircraft encounters a downdraft. Motion rate sensors will respond at the instant aircraft motion occurs. The output of the sensors will result in an η_{ld} that deflects the symbol down. To keep the symbol on the aimpoint ($\eta_{se}=0$), the pilot reacts, correcting upward. Note that a potential glidepath error, which can result from downdraft, is anticipated by motion rate sensors and converted into aircraft symbol motion, leading the pilot to correct before a deviation from glidepath can become significant. This is the essence of a feedback compensated control system.

Lead compensation η_{ld} can be generated in many ways; Fig. 6 shows one example. Simpler designs would be adequate. The altitude gain scheduling shown is desirable but not necessary. The A_n input, in addition to $\dot{h}$, provides only small improvement. Another modification is the substitution of A_n for $\ddot{h}$. (Note that $s\dot{h}$ is considered approximately equal to A_n.) If an A_n measurement is available on the aircraft, its substitution for $\dot{h}$ eliminates the problems normally associated with static port measurements.

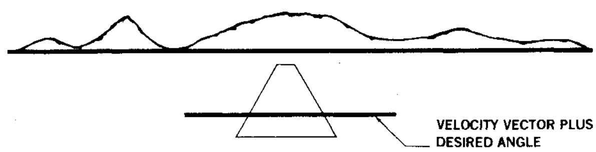

Fig. 3 Combined display.

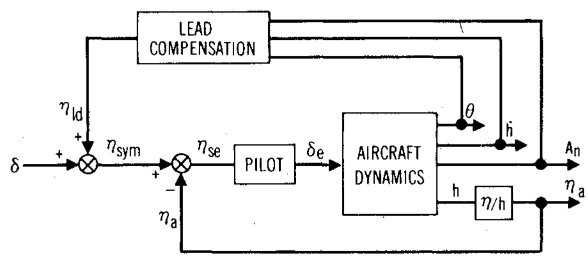

Fig. 4 Block diagram of a compensated control HUD system.

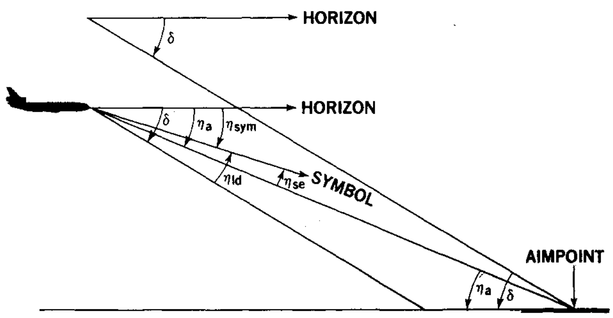

Fig. 5 Compensated control angle relationships.

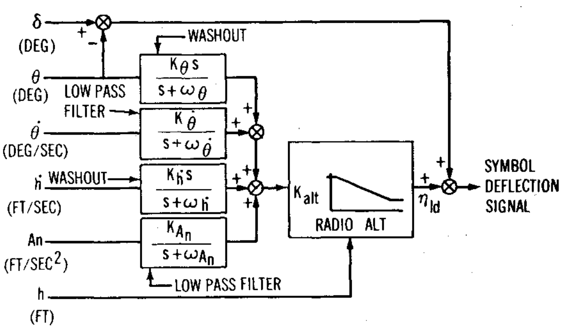

Fig. 6 Block diagram of a lead design for compensated control HUD.

The computation of η_{ld}, as shown in Fig. 6, is accomplished in the following manner:

1) θ aids pitch stabilization for phugoid damping.

2) Steady-state θ is washed out over a period that is long, relative to the aircraft's dynamics.

3) $\dot{\theta}$ adds lead damping to pitch control.

4) The filter shown for $\dot{\theta}$ is a noise filter for frequencies above aircraft dynamics.

5) $\dot{h}$ provides path control rate damping.

6) Steady-state $\dot{h}$ is washed out over a period that is long, relative to the aircraft's dynamics.

7) A_n, with its noise filter, contributes higher-order lead.

The subtraction of θ from δ is a requirement of all HUDs (either directly or indirectly) to remove aircraft pitch from the display, so that the display remains fixed with respect to the horizontal. Some have made the mistake of thinking that the washed-out $\dot{h}$ combined with the lagged A_n is a complementary filter; however, the washout frequency is an order of magnitude slower than the lag frequency, not the same frequency as in a complementary filter.

Experience has shown that it is necessary to explain the differences between the compensated control HUD and the $\delta\gamma$ HUD. (The $\delta\gamma$ HUD combines the desired descent angle δ with the velocity vector γ.) To point up the difference in dynamic response, a heuristic examination will be used. To facilitate comparison, the form of the control laws is changed as follows: By definition,

$$(\eta_{\text{sym}})_{\delta\gamma} = \delta + K_{\delta\gamma}(\gamma + \delta) \tag{1}$$

For the small angles under consideration,

$$\gamma = \dot{h}/V \qquad \delta = \dot{h}_\delta / V$$

Substituting in the second term of Eq. (1)

$$(\eta_{\text{sym}})_{\delta\gamma} = \delta + (K_{\delta\gamma}/V)(\dot{h} - \dot{h}_\delta) \tag{2}$$

By definition,

$$(\eta_{\text{sym}})_{\text{comp}} = \delta + \eta_{ld}$$

If the compensated control lead parameters η_{ld} are limited to the washed-out $\dot{h}$,

$$(\eta_{\text{sym}})_{\text{comp}} = \delta + K_{\dot{h}}[s/(s+\omega_{\dot{h}})]\dot{h} \tag{3}$$

Also, to aid comparison, V is considered constant:

$$K_{\delta\gamma}/V = K_V$$

Substituting in Eq. (2),

$$(\eta_{\text{sym}})_{\delta\gamma} = \delta + K_V(\dot{h} - \dot{h}_\delta) \tag{4}$$

Consider this example: An aircraft that has been steadied on the selected glideslope δ encounters a change in vertical wind, which causes a change in vertical speed $\dot{h}$. Compare the dynamic responses of the two control laws by observing the responses of Eq. (3) and (4) following the upset in $\dot{h}$ and prior to another input such as pilot action:

1) $(\eta_{\text{sym}})_{\delta\gamma}$ will have a new constant value after the upset.

2) $(\eta_{\text{sym}})_{\text{comp}}$ initially will change value by the same amounts as $(\eta_{\text{sym}})_{\delta\gamma}$.

It is this same initial response that leads some to conclude that the two control laws are similar. However, the two responses become increasingly divergent following the initial upset. While the $\delta\gamma$ symbol continues pointing in the same direction, the direction the compensated symbol points will change until it points in the direction of the desired descent angle δ, i.e., the $\dot{h}$ upset washes out at the time constant $1/\omega_h$.

The basic character of the compensated control HUD is to return control always to the desired descent angle δ. The lead η_{ld} provides a *temporary* signal to indicate the trend of a potential error, leading the pilot to take corrective action.

The pilot's response to the $\delta\gamma$ HUD will cause a change in the computed γ, i.e., $\dot{h}/V$ changes. If the computation of γ is precise, actual altitude rate $\dot{h}$ will eventually become equal to $\dot{h}_\delta$ after an iterative series of corrections by the pilot, at which time $(\eta_{\text{sym}})_{\delta\gamma}$ will equal δ. If the computation of γ is in error by an amount equal to γ_e, the pilot will be controlling the aircraft to a glideslope angle that will differ from the desired angle δ by $[K_{\delta\gamma}/(1-K_{\delta\gamma})]\gamma_e$. Observe that the smaller the value of $K_{\delta\gamma}$, the less susceptible to γ error; but the tradeoff is less rate-damping. The magnitude of $K_{\delta\gamma}$, which must be less than 1, determines the proportion of γ relative to δ ($k_{\delta\gamma} = 0.25$ means 25% γ relative to 75% δ).

The compensated control HUD will direct the pilot through wind shear down the desired approach path.

HUDs used for instrument approaches have been improved over the years to provide displays that are conformal with visual cues. The compensated control HUD is adapted to the instrument approach. This adaptation, in conjunction with visual perspective computation derived from ILS signals, provides a fully conformal display.

DC-9 Super 80 Head-Up Display

To achieve wide acceptance, the HUD must have the following characteristics: 1) uncluttered symbology, the meaning of which is so intuitive that no confusion will be induced even under stress; 2) minimal training necessary to achieve proficiency; 3) a dynamic response that is easy to follow; 4) accurate guidance; and 5) safe guidance through wind shear.

The DC-9 Super 80 HUD has fulfilled these requirements through these means: 1) the compensated control law; 2) development of control laws for a simple, meaningful display[5]; and 3) optimization of symbology according to inputs accumulated from pilots during years of fixed- and motion-base simulator flying using the HUD in all possible conditions.

The prime guidance symbol in the DC-9 Super 80 HUD is an aircraft symbol that banks and turns as the aircraft banks and turns; the wings of the aircraft symbol remain parallel to the wings of the aircraft itself. The pilot "flies" the aircraft symbol toward the runway touchdown zone. If he is approaching a runway where an ILS is available and cannot see the runway, a small circle (aimdot) is included in the display to show the direction of the runway touchdown zone. As the runway becomes visible, he will see the aimdot superimposed on the actual runway touchdown zone (Fig. 7). During an instrument approach, the appearance, motion, and location of HUD symbols are designed to give the pilot the same cues that he uses during visual flight. This serves two purposes: 1) his response to HUD cues is intuitive; and 2) since the same concepts are used in both the instrument and the visual HUD, no conceptual transition is required between instrument and visual flight. Because the display directly corresponds with the real world, the available ground cues (that are increasingly visible as he proceeds from instrument to visual conditions) directly complement the HUD display. If a pilot holds the aircraft symbol on the touchdown zone, his aircraft will acquire and proceed down a predetermined approach path.

Also, symbology is provided so the pilot can continuously monitor his position relative to the category II ILS tolerance window. An ILS box is drawn on the display to represent permissible localizer and glideslope deviation (Fig. 8). Below 100-ft radio altitude, the box is replaced by computer-generated runway sidelines which represent a 150-ft-wide runway in perspective. If, during an autopilot approach, the autopilot should be disconnected intentionally or because of equipment failure, the warning TAKEOVER would flash in the area below the aircraft symbol.

When the aircraft approaches the flare altitude, the aimdot (which is always in the instrument approach display) will appear in the visual approach display. After a warning flash, the aimdot will move up, commanding a flare computed from altitude and rate of descent. By keeping the aircraft symbol on the aimdot, the pilot is directed to a soft touchdown. Rollout displays are provided in both instrument and visual modes, and under both conditions the aircraft symbol is displayed at a fixed angle below the horizon. During the visual landing, the flare command function of the aimdot is completed at touchdown and is blanked out of the display while the aircraft symbol is fixed to aircraft heading, thus assisting in rollout when held on centerline. In an instrument landing, after flare and touchdown the aimdot and runway edge lines continue to provide lateral guidance to supplement visual cues.

The head-up display is designed to provide pitch and heading-hold guidance during takeoff or go-around (TOGA). This mode is initiated by depressing the TOGA throttle palm switches. TOGA is then annunciated above the right wing of the aircraft symbol.

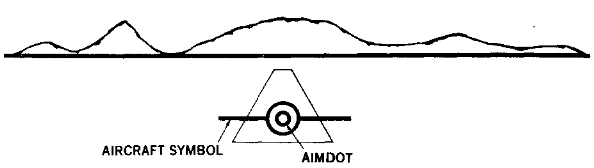

Fig. 7 DC-9 Super 80 HUD guidance symbology.

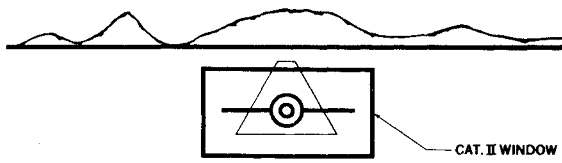

Fig. 8 DC-9 Super 80 HUD indicating ILS limits.

System Description

The DC-9 Super 80 Head-Up Display System consists of three line-replaceable units: one computer, one control panel, and one pilot display unit (PDU) (Fig. 9) There also is an optional first officer's PDU available.

The computer is a rack-mounted unit to ARINC 404A standard. It weighs approximately 15 lb and has an estimated reliability of 4200 h MTBF. It is a high-speed 16-bit bipolar computer which provides all the necessary computation for symbol generation, control law mechanization, and system monitoring.

Input sensor data can be accepted in discrete, digital analog, or synchro form. Suitable conditioning and multiplexing of these signals is performed within the computer under the control of the central processing unit (CPU). The control law processing is also carried out in the CPU, and the resulting commands are output to the symbol generator. The symbol generator, contained in a separate part of the computer, provides the instructions necessary to generate the signals for CRT presentation of the correct symbol format. The computer iteration time is 60 ms. The unit is capable of driving both PDUs.

The PDU is a compact, modularized, overhead-mounted cockpit element which contains the HUD optics, CRT, associated electronics, and optics stow mechanism. Accelerometers are also installed within the PDU and provide outputs used by the computer. The PDU permits the pilot to receive important aircraft flight-guidance information in the same field of view as the outside world; it provides a flexible display format through use of electronic symbology writing techniques, large field of view, and automatic maintenance of display brightness contrast. The display is refreshed every 20 ms. With the optical element in the stowed position, neither pilot's field of view is obstructed. PDUs are replaceable without realignment being necessary. In addition, the map light, cockput speaker, and conditioned air outlet are incorporated as integral parts of the unit.

The control panel is located in the pedestal between the pilots and incorporates a thumbwheel (which is used to select the desired flight-path angle), a radio altimeter/barometric altitude switch, and a switch which permits the pilot to perform a system confidence self-test.

The entire system integrates into the existing DC-9 Super 80 Digital Flight Guidance System (DFGS) as described by

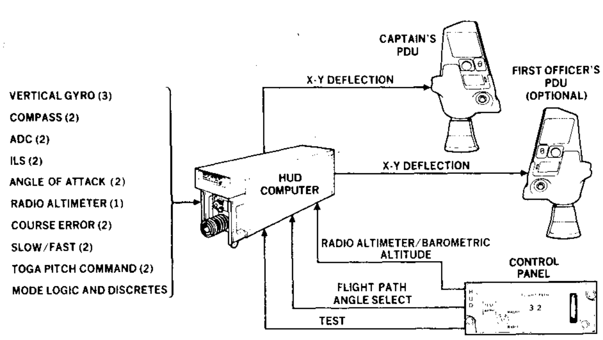

Fig. 9 DC-9 Super 80 HUD system.

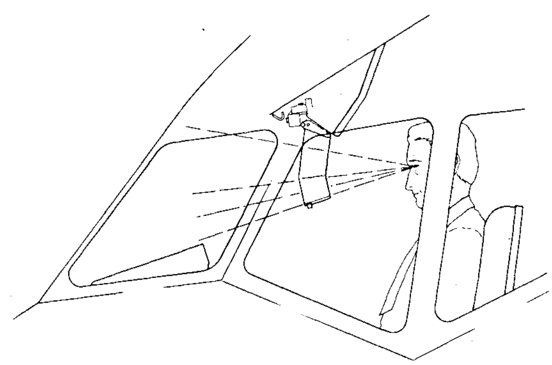

Fig. 10 Pilot display unit (PDU).

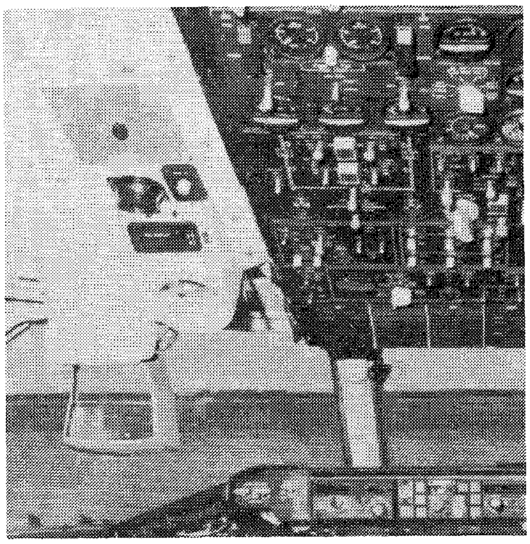

Fig. 11 Captain's PDU in operating position (first officer's unit opposite).

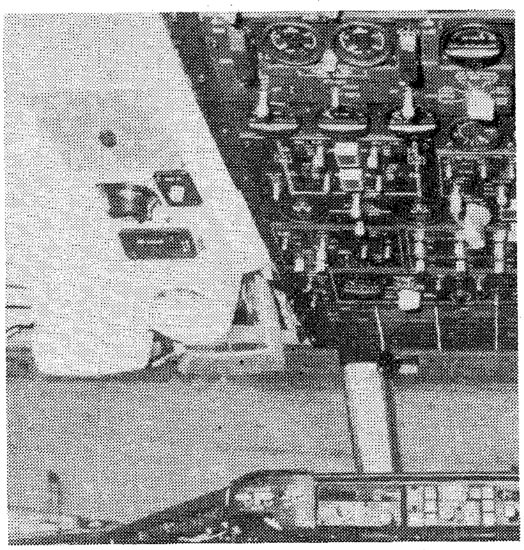

Fig. 12 Captain's PDU in stowed position.

Armstrong and McDonnell[6] and as a prime guidance system certified for CAT I, II, and VFR conditions.

System Monitoring

The effectiveness of any HUD system depends on the success achieved in maintaining display integrity. The DC-9 Super 80 HUD met its goal of being a fully monitored system by performing these functions: 1) monitoring to detect any fault which would affect the ability of the computer to correctly process data; 2) monitoring of the sensor input data to detect any invalid input data; and 3) monitoring of the PDU electronic output to detect any error in positioning the symbology. All for the monitoring sequence is repeated every computer cycle, i.e., every 60 ms.

In conjunction with the electronic monitoring, PDU optics position is monitored by self-test and lens-mounted accelerometers. The pilot performs a system confidence self-test before or during flight. The alignment verification is performed by comparing the position of a displayed fixed-reticle with the CRT- displayed image. A flashing CRT image or no image indicates a system malfunction.

Pilot Display Unit (PDU)

One of the most difficult tasks in developing a HUD for commercial transports is to provide an optics system for

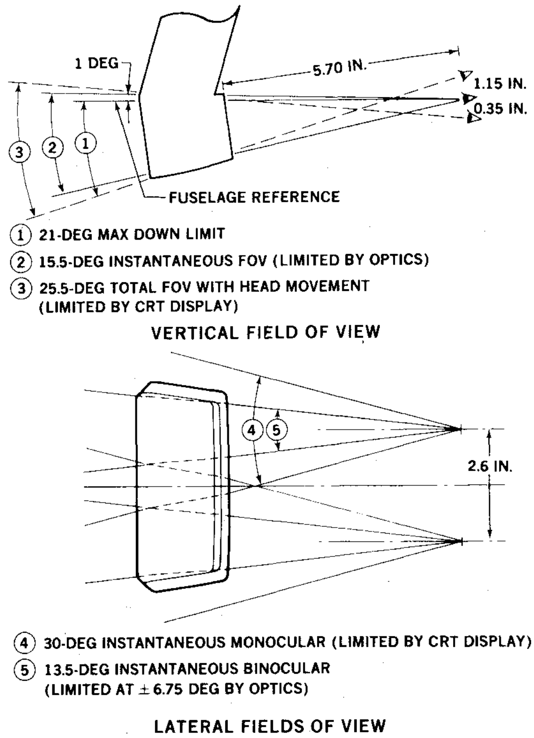

Fig. 13 PDU optics field of view.

maximum viewability that will fit into the small area provided in a cockpit. This was accomplished in the DC-9 Super 80 using a Sundstrand designed PDU.

The PDU utilizes a solid optical lens system. The optics are constructed of solid optical quality acrylic resin that is precision-machined and lapped to provide clarity and low distortion of the background view and the displayed image. The solid path system uses an on-axis spherical mirror to reflectively collimate the display image to project it to near infinity. A diagonal beam-splitter combines the collimated image with the background view. The solid path system has the optical advantages of a mirror collimated system, i.e., simplicity, low distortion, freedom from chromatic aberration, and wide field of view. Its solid construction has the additional advantages of ruggedness, freedom from opaque supporting structure, and an optical magnification factor that reduces the size of the optical path between the mirror and the CRT, thus reducing the size of the focal plane at the CRT face. The optical magnification factor allows the use of a 3-in. CRT with a relatively small optical block to produce large vertical and horizontal fields of view.

Figures 10-12 show the PDU installed in the DC-9 Super 80 cockpit. It should be noted that in order to make the PDU a line-replaceable unit (LRU), the mounting points have to be very accurately maintained. Also, the PDU assembly must be very precisely built to maintain system accuracies. It should be noted that the PDU must have the map light, speaker, and air outlet as a part of the basic unit in order to fit in the already defined cockpit space.

Figure 13 shows the wide field of view of the optic system.

Symbol Presentation

Symbols presented to the pilot are generated electronically by programmable digital implementation. All symbols used are continuously computed, position-updated, and electronically projected to the face of the cathode-ray tube and, through the use of an immersed optics systems, are presented to the pilot. This information is superimposed in the pilot's forward field of view. Although all symbols are continuously written, only those symbols applicable to the present mode of operation are visible. All others are blanked (Fig. 14).

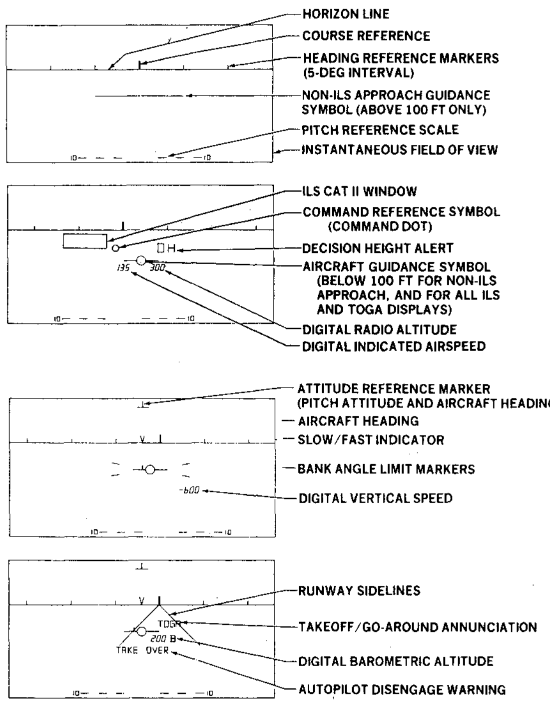

Fig. 14 DC-9 Super 80 HUD symbology.

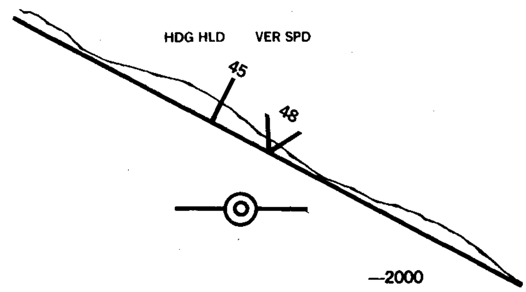

Fig. 15 Heading hold and vertical speed modes.

Areas of Potential Growth

Terminal Area Guidance Using the HUD

With existing HUDs, the pilot uses the panel instruments to bring the aircraft near the approach path, then uses the HUD to complete the approach. Terminal area guidance using a HUD will allow him to be head-up before reaching the runway approach. This aids collision avoidance, facilitates short approaches, and implements noise abatement procedures such as the two-segment approach. The terminal area HUD should provide guidance for entering the terminal area, and intersecting and capturing the approach path. This requires additional cruise modes such as vertical speed, altitude hold, and heading hold, as well as glideslope capture and localizer capture.

The terminal area HUD should perform the following functions: 1) transition smoothly into the approach HUD; 2) use the same symbology and control philosophy as the existing HUD; 3) be totally conformal with the visible world; 4) keep the command symbology always within the field of view; and 5) have no symbol jump when transferring between modes.

It is apparent that these requirements cannot be met with the flight director signals. The principal challenge is to keep the command symbology within the field of view. A terminal area HUD prototype that fulfills all of the stated requirements is currently being flown on simulators at Douglas. If the aircraft is in the vertical speed or altitude hold mode and the heading hold mode, the selected parameters will be held constant as the pilot controls the aircraft to hold the aircraft symbol on the aimdot. An asymptotic capture of selected altitude, glideslope, and localizer is commanded. During heading select and localizer capture the aircraft is commanded to hold a constant selected bank angle until heading or localizer is captured. Two mode annunciations appear in the display. As the guidance automatically proceeds from one mode to the next, lateral annunciation (displayed to the left) changes from HDG SEL to HDG HLD to LOC CAP to LOC TRK, while on the right, longitudinal annunciation changes from VER SPD to ALT CAP to ALT HLD to G/S CAP to G/S TRK. For example, the pilot selects a 45-deg heading and a vertical speed of −2000 ft/min. As he holds the aircraft symbol on the aimdot, the aircraft turns toward the 45-deg heading at a selected bank angle and descends at 2000 ft/min. As the turn continues, the 45-deg heading appears in the field of view; as 45 deg is approached, the aircraft is directed to turn onto this heading without overshoot. The symbology in Fig. 15 indicates that the aircraft is passing the 48-deg heading. In the same manner, when the localizer is approached, the pilot banks the aircraft to a selected bank angle in order to hold the aircraft symbol on the aimdot. As the turn continues, the bearing of the runway moves into the field of view; as the proper aircraft heading (which depends upon the amount of crosswind) is approached, the aircraft is directed to turn onto the approach and continue tracking the localizer.

Precise Heading and Attitude Reference

The alignment that the pilot sees between the HUD symbology and the real world is dependent upon the accuracy of the measurement of aircraft heading and attitude. This is a characteristic of all HUDs. As HUDs become more sophisticated in duplicating the real world, an apparent misalignment becomes more disturbing to the pilot. During an instrument approach, the misalignment with the real world constitutes no problem so long as the pilot does not see the runway. The HUD symbology commands the pilot down the ILS approach path irrespective of the location of the symbology relative to the real world. Though the symbology duplicates the real world, its commands are independent of the outside view.

Attitude and heading errors caused by vertical gyros and compass systems may occur when an aircraft is maneuvered in a particular manner. The vertical gyro (which approximates the true vertical by referencing inertial force measurements) erects to a false vertical, according to its erection characteristic, following a prolonged acceleration; this translates into a pitch error. In a similar manner, the directional gyro, referenced to a magnetic compass, will pick up directional errors from particular turn maneuvers.

These attitude and heading errors are small enough to have been tolerated previously for autopilot and HUD use. Now, because runway edge lines are included in the HUD, a gyro error, particularly a directional error, is directly observable by the pilot in the misalignment between the HUD runway and the real-world runway. What the pilot sees is an error. It is difficult for him to reconcile this with the fact that what he sees is only a *viewing* error, which has no effect on the accuracy of the path commanded by the HUD. In a visual approach, where an ILS is not used, the relationship between the display and the real world is not apparent, therefore the pilot is unaware that he is flying an angular error. In this case the error is real; however, it will converge to zero as he flys to his aimpoint.

This misalignment between the HUD runway edge lines and the real-world runway has caused complaints from commercial pilots. The latest attitude and heading reference systems can improve the accuracy of the display orientation, thereby providing better real-world duplication.

Conclusion

It has been demonstrated in commercial aircraft that a HUD can be designed to guide a pilot through wind shear and down the desired approach path with a fraction of the work load now tolerated, even though the pilot has little previous HUD experience. This is accomplished with feedback compensated control laws and with display commands that are intuitively obvious. The addition of cruise modes extends the HUD approach function to include guidance for entering the terminal area and capturing the approach path.

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