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Flight Test Certification of Multipurpose Head-Up Display for General Aviation Aircraft

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Advances in flight display technology have enabled manufacturers to provide a head-up display (HUD) of aircraft control and performance parameters for use in general aviation aircraft without the use of inertial platforms or specialized data bus architecture. The Federal Aviation Administration currently has no regulatory guidance regarding HUD or flight symbology certification. A specific certification program is presented. The process of categorizing the HUD as a supplemental system instead of a primary display is discussed. Flight display symbology is discussed, and the final symbology set is presented. The certification flight test plan is discussed including the requirements for functional, usability, and operational testing. Flight test data are discussed. A HUD system was certified for single-pilot use in instrument meteorological conditions in a general aviation aircraft.

Introduction

THE head-up-display (HUD) was first developed in military aircraft from reflecting optical sights. The HUD places flight and navigation data in the pilot's forward field of view (FOV). These data are presented through various symbols as a collimated image that appears to be floating at infinity. Early HUDs were used for weapons delivery with displays tailored for a single task. HUDs today can provide a variety of aircraft state and navigation data. Recent HUD development, as an enhancement tool to facilitate manually flown instrument approaches to weather minima as low as a runway visual range of 1200 ft, has obvious implications for air carrier operations. The ability to ease the instrument-to-visual approach transition and acquire the runway environment sooner is a desirable feature of any cockpit display system. Though these systems usually require high-fidelity inertial reference platforms and are costly, the advantage gained in arrival reliability has been deemed cost effective. Additionally, because the pilot has state and navigation data available while looking through the aircraft windscreen, the increased ability to visually clear for other traffic is a safety enhancement. Current HUD development and operational concept are toward displays that are useful and certifiable during all phases of flight. Lower cost displays that do not provide enhanced capability, but do provide increased out-of-the-cockpit awareness for corporate and general aviation aircraft are also emerging into the marketplace.

A typical HUD displays airspeed, altitude, pitch and roll attitude, and heading. In addition, navigation or mission data can usually be selected for display. Flight director modes, radar altitude, and marker beacon passage can also be shown, if available. Most HUDs can also display master warning and caution annunciators.

The subject HUD was targeted for the corporate and general aviation industry. This HUD differed from other operational systems in that it used conventional aircraft gyros and did not depend on an inertial navigation system platform for attitude information. Since conventional aircraft gyros are less precise than inertial platforms, the HUD symbology was not conformal in that the symbology does not align directly with real-world horizon cues. To minimize subjective discomfort, the HUD symbology was compressed relative to the real world. This had the added benefit of enhancing pilot spatial orientation, by reducing the rate at which pitch scale translates during maneuvering, and enabled the horizon reference line to remain in view throughout most of the flight envelope.

The subject HUD was initially intended for use as a supplemental flight display designed to enhance flight safety, by allowing the pilot to refer to flight data and either clear the flight path for traffic, or acquire the runway environment during an instrument approach, simultaneously. The aircraft had a full complement of conventional panel instruments as required by the appropriate certification and operating rules. In the event of HUD failure or a detected sensor failure, the HUD ceased displaying the appropriate information and the pilot reverted to the head-down display (HDD) instruments for missing flight information.

Prior to the certification flight test program, an extensive symbology development program was flown in a light aircraft equipped with the HUD. This program resulted in a symbology set that was found satisfactory for all phases of flight, with the exception of low-visibility instrument approaches such as categories II and III instrument landing system (ILS) approaches. It should be kept in mind that this report only details flight test requirements, objectives, and results. Systems, equipment, and airframe requirements and certification efforts are not discussed, but have importance in any certification program of this nature.

Objectives

General Objective

The overall objective of the flight test program was to certify a head-up display installation in a corporate aircraft under a supplemental type certificate. The HUD was intended to be a supplemental display providing flight and navigation information to the pilot and to be used during both visual meteorological conditions (VMC) and instrument meteorological conditions (IMC). Through the flight test, the applicant was required to show that the pilot could control the aircraft to acceptable tolerances using the HUD in concert with HDD instruments and that any invalid data were clearly annunciated to the pilot.

Specific Objectives

The specific objectives of this test program demonstrate the following:

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1) The HUD provided an adequate navigation display to allow a pilot to fly an instrument approach.

2) The pilot could safely execute the transition to visual conditions during an instrument approach, and he could safely land the aircraft or transition back to instrument flight and execute the published missed approach procedure using the HUD.

3) The pilot could fly to acceptable enroute instrument flight rules (IFR) accuracy using a navigation signal displayed on the HUD.

4) The pilot could recognize and recover from unusual attitudes using the HUD and panel-mounted instruments or using the panel instruments alone after detecting a HUD failure.

5) The HUD had no adverse effect on aircraft systems with all systems operating.

6) The HUD displayed accurate flight parameters (airspeed, altitude, magnetic heading, etc.) and annunciations (master caution, altitude alert, etc.).

7) The HUD provided adequate warning in the event sensor data were missing or sensed to be invalid.

8) The HUD system performed satisfactorily during typical operations.

Test Equipment

HUD

The HUD system consisted of three line replaceable units. These were the pilot display unit, the pilot control unit, and computer unit. All units were inspected and conformed to the type design data prior to the start of the certification flight test.

Aircraft

The host aircraft for the certification program was a corporate turboprop aircraft. Prior to the beginning of flight testing, the aircraft was thoroughly inspected and conformed to the original type design data. Additionally, the HUD installation was conformed on the aircraft to the installation design data.

Vision Restriction System

A complementary color vision restriction system was installed in the airplane to simulate IMC, allow the evaluation pilot to view the HUD, and not restrict the view of the safety pilot. The system consisted of a red film over the windshield and side windows. The view through the film was colored, but was found satisfactory for safe aircraft operation. During flights requiring vision restriction, the evaluation pilot wore green goggles. The view of the cockpit interior and HUD symbology was unaffected, while external visual cues were blocked by the complementary color filters.

Data Recording and Analysis

Aircraft Data

Aircraft position was determined using onboard navigation receivers, panel instruments, and visual ground references, as appropriate. Position data were hand recorded, as required. The pitot–static system, airspeed indicators, and altimeters were calibrated. All radio navigation equipment was also calibrated.

HUD Data

Specific pilot observations were required to ensure that no adverse HUD-induced effects were present. These observations were prompted by a general observations rating card used on all flights. In addition, specific tests were flown asking for specific problem areas, such as the presence or absence of light reflections during night operations. During instrument approaches, the HUD output was recorded. A laptop computer was used to capture the HUD data stream for postflight analysis. Additionally, simulated faults and sensor failures could be injected into the HUD through the laptop computer. It was not possible to record data during those approaches with simulated sensor failures.

Other Data

During instrument approaches, the weather conditions, specific approach flown, and outcome of the approach were documented on an approach rating card. A display rating scale, based on a derivative of the Cooper–Harper pilot rating scale, was used to rate HUD readability and controllability during specific tasks.[1] The use of this type of subjective rating scale requires the definition of specific flight tasks and performance criteria. Such tasks and criteria were derived from previous military HUD certification programs.[2] An example of a specific flight task would be localizer lateral course tracking during an ILS approach. The desired performance criteria for localizer course tracking was to track the course within one-half dot deflection on the course deviation indicator. Satisfactory performance was tracking the course within one dot deflection on the course deviation indicator. Evaluation pilots completed a rating card at the conclusion of the task. Readability and controllability were rated based on a flow chart of usability decisions and task outcomes based on the performance level achieved.

Test Procedure

Before testing could begin, the HUD system had to be categorized according to the intended use sought by the applicant. Properly categorizing a HUD as a primary or supplementary flight display is essential when building a certification test plan. The HUD was categorized by the Federal Aviation Administration (FAA) Small Airplane Directorate as a supplemental flight display, and the certification flight test program was built accordingly. Certification tests were grouped into three areas: 1) system functional tests, 2) pilot interface tests, and 3) operational tests. The airplane flight manual supplement (AFMS) was evaluated throughout the test program.

Supplemental Flight Displays

This HUD was designed as a safety enhancement device to repeat HDD flight information into the HUD FOV. The intended use was to allow the pilot to perform climb, cruise, and approach operations. Using the HUD in concert with HDD instruments was intended to facilitate head-up tasks, such as clearing for traffic and identifying airport and runway environments. The HUD was not intended to be used as an independent guidance system or an enhanced approach tool. It was only a repeater of conventional panel instrument information into a HUD system. Using this approach, the HUD was merely a repeater device, and no extra capability or operation unique to the HUD was provided or sought by the applicant. The fundamental differences between primary and supplemental displays lie in two areas: 1) warning annunciation and 2) display symbology. Although feasible, this HUD was not designed to be used as a stand-alone instrument system. Hence, head-down cross-checking of navigation information, engine indications, and flight director annunciators was still required. The HUD system was not considered as a replacement for HDD instruments, but as a tool to aid in the transition to the head-up environment. Additionally, not all of the information required to fly and monitor the aircraft in a totally head-up environment was available. Head-down cross-checking of engine instruments, system annunciations, and verification of flight instrument setup was essential. The failure warning and annunciation scheme implemented was sufficient to alert the pilot to check HDD annunciations to further analyze system anomalies. When preparing to fly instrument approaches, HDD instruments were tuned, set, and cross-checked with HUD indications to ensure proper approach setup. Although it was possible to control the aircraft by sole reference to the HUD, proper systems cross-check and engine monitoring was not possible. HUD use in this manner was not intended by the applicant.

Although the intent was to install the HUD as a supplementary display, environmental qualification testing in accordance with the Radio Technical Committee for Aeronautics (RTCA) DO-160C included complete environmental tests, such as susceptibility to high-intensity radiated fields (HIRF) and the indirect effects of lightning.[3] Software qualifications were done in accordance with RTCA DO-178B required for software considered essential.[4] This level was deemed acceptable since the HUD was designed as a repeater of information from the primary flight instruments and not as a primary flight instrument.

The coordinated FAA position was to treat this HUD as an aid to head-up aircraft control that is not a primary flight instrument system. The system would be certified as a supplemental system with an equivalent level of safety to a conventionally designed cockpit.

System Functional Tests

System functional tests were designed to ensure the HUD accurately transmitted and displayed data through the HUD. Accurate display of data from the HDD instruments was considered an essential requirement when evaluating system performance of intended function and determining equivalent levels of safety. The reception and accuracy flight test profiles, described in the FAA Flight Test Guide, were used as a basis for evaluating the functional areas listed as follows[5]: navigation aid accuracy, navigation aid tracking, navigation aid station passage, ILS localizer course intercepts, automatic direction finding (ADF) indicator response when switching between stations, pitch and roll response of the attitude display during a variety of maneuvers, air data accuracy, systems and electromagnetic compatibility, and HUD interpretation of sensor failures.

Pilot Interface Tests

Pilot interface tests were designed to evaluate the pilot/HUD interface in several areas such as display readability in various lighting conditions and optical deficiencies such as flicker or glare; dynamic deficiencies such as jitter, noise, and excessive lead or lag; in-flight initialization; engine failure; unusual attitude recognition and recovery; sensor failure recognition; HUD modes of operation; command carets; traffic detection; and precision and nonprecision instrument approaches.

Subjective pilot ratings. Several tests required subjective pilot ratings or pilot observations. These tests centered on the usability of the HUD symbology.

Display ratings. As described earlier, a display rating scale based on a derivative of the Cooper–Harper pilot rating scale was used to rate the HUD during instrument approach tasks. The use of this scale required the definition of specific flight tasks and performance criteria. Such tasks and criteria were also described earlier.

Pilot observations. Specific pilot observations were required to ensure that no adverse effects were present. Observations were prompted by a rating card that was used on all flights. After accomplishment of each task, the evaluation pilot was interviewed by the safety pilot to capture appropriate observations.

Instrument approaches. During instrument approaches, the weather conditions, specific approach flown, and outcome of the approach were documented by the safety pilot on an approach rating card. During this phase, evaluation pilots flew published standard instrument approach procedures. All approaches were flown in simulated or actual IMC. Half were flown to touchdown and half to missed approach. Several different approaches were flown to minima at different airports. Twenty such approaches of each type were flown for which approval was sought. Two approaches of each type were flown with a simulated engine failure during the approach. Half of all ILS approaches were flown using raw data and half using flight director guidance. Additionally, 10 approaches were flown to circling minima, followed by a circling maneuver through at least 180 deg to a landing. Half were flown at night. Two circling approaches were flown with a simulated engine out. The approach flown, weather conditions, landing or missed approach, and success or failure of the approach were recorded. To ensure uniformity in data gathering, all approaches were flown with approach flaps and a reference airspeed of 120 kn. Approaches were flown using a combination of HUD and HDD instruments. Procedures and techniques for optimum use of the HUD in concert with HDD instruments were developed during flight test and incorporated in the AFMS.

Operational Tests

An operational evaluation of 20 h was planned in high-traffic density areas to evaluate HUD performance in operationally representative environments. Fifteen of these hours were to be flown with representative operational pilots flying the aircraft. Data recording equipment was not required for these flights. The following criteria were applied to meet the operational test objectives:

1) There were no local flights.

2) At least two flights were into primary airports with FAA class B airspace (two arrivals and two departures).

3) At least two flights were into uncontrolled airports (two arrivals and two departures).

4) Credit for up to 15 min of cruise per flight in VMC was included in the 20 h. Up to 1 h in IMC per flight was included in the 20 h. To be credited, the cruise flight time was hand-flown.

5) There were at least five flights using single-pilot procedures and at least five flights using two-pilot procedures.

Airplane Flight Manual Supplement Evaluation

During all phases of certification flight tests, a concurrent evaluation of the adequacy of the AFMS was made. All evaluation pilots were asked to comment on the suitability of the material. Particular emphasis was placed on limitations, systems description, and system operation.

Safety Issues

Flight Test Specific Hazards

The risks peculiar to flight test were the possibility of HUD-induced instrument or radio failure during instrument flight and HUD-induced loss of situational awareness. Before flight in actual IMC, sufficient VMC system testing was conducted to provide confidence in the HUD system and use of the HUD. Another risk was the possible loss of control during simulated engine-out flight. Project safety pilots were experienced instrument and multiengine flight instructors and were responsible for the safety of flight during these tests. The safety pilots had a full complement of flight instrumentation available on their side of the cockpit to ensure that they were able to monitor the flight and take aircraft control, if necessary, without having to refer to flight instruments in a cross-cockpit fashion.

Precautions Required

Anticollision lighting and landing lights were used at all times in the instrument pattern. Before flight into actual IMC, a safety review was conducted to ensure confidence in the HUD systems to be evaluated. For flights with the vision restriction system installed, an extra observer was used to supplement the safety pilot's view on the left side of the airplane.

Test Results

System Functional Tests

The HUD functional flight profiles followed the reception and accuracy profiles described in the FAA Flight Test Guide.[5] Specific areas are described next.

VHF omnirange receiver (VOR) display. The VOR navigation accuracy tests were flown over several VORs to confirm the calibration in four quadrants. In both clean and approach configurations, the indicated radials were within 2 deg of the actual radial. The HUD indicators agreed with both HDD indicators and both VOR receivers.

ADF display. The ADF accuracy test was accomplished in clean and approach configurations (gear down, flaps approach). The ADF bearing on the HUD agreed with both cockpit indicators. All indicators were approximately 8 deg in error. The ADF was returned to the shop and calibrated. Following calibration, all indicators agreed within 1 deg of the sensed bearing.

VOR tracking. The VOR course width test was flown over VOR stations that permitted cross-tuning of several different facilities. The course width in all cases was 20–21 deg. Both clean and approach configurations were evaluated. No navigation flags were displayed. The HUD display agreed with the cockpit HDD.

ILS localizer tracking. Localizer courses were flown at four different airports. The localizer behavior was examined throughout the final approach at 10–12 mile from the airport. In all cases, the localizer behaved normally with correct sensing. The evaluations were flown in clean and approach configurations. No navigation flags were displayed. The HUD display agreed with the cockpit HDD.

ILS glide slope tracking. ILS glide slopes were flown at three different facilities. Glide slope behavior was examined from the final approach fix to decision height. In all cases, the glide slope behaved normally with correct sensing. The evaluations were flown in clean and approach configurations using normal pitch and roll attitudes. No navigation flags were displayed. The HUD agreed with the cockpit HDD.

Flight director. ILS approaches were flown at three different facilities. Flight director behavior was examined throughout the final approach beginning at 10–12 mile from the airport. The flight director behaved normally with correct sensing. The evaluations were flown in clean and approach configurations. The flight director behavior was also examined on a course from 5 mile on either side of the VOR through to the opposite course. In all cases, the flight director behaved normally with correct sensing. The evaluations were flown in clean and approach configurations. The HUD display agreed with the cockpit HDD.

Station passage (VOR, ADF, and marker beacon). Course deviation behavior was examined on a course from approximately 5 mile on either side of the VOR through to the opposite course. In all cases, the deviation behaved normally with correct sensing. The evaluations were flown in clean and approach configurations. The HUD agreed with the cockpit HDD. ADF station passage was evaluated in clean and approach configurations. The indicator made only one complete reversal during station passage. The marker beacon annunciation in the HUD agreed with the head-down marker beacon lights. Tests were accomplished using several ILS procedures to evaluate outer and middle marker signals.

ILS localizer intercept. This evaluation was flown at three facilities examining ILS courses in both clean and approach configurations. Course widths and behavior agreed between the HUD and the cockpit HDD. No navigation flags were evident between the extreme course widths. The HUD display agreed with the pilot's HDD.

Indicator response (ADF). The ADF receiver was switched between several ADF stations. The indicator correctly responded within 10 s while switching between stations.

Pitch and roll response. The HUD pitch and roll display was evaluated during the following maneuvers: full-flap instrument and visual approaches, go-arounds, steep turns, emergency descents, and single-engine operation. These tasks were flown solely by reference to the HUD when possible. During turning flight with simulated engine failure, it was difficult to manage sideslip using only the HUD, and reference to the HDD sideslip indicator for accurate directional control was required. As a result, the AFMS was written to require the pilot to recover from an engine failure head-down, retrim, and then use the HUD, if desired. The emergency descent was difficult using the HUD alone. Precise airspeed control to maximize the descent rate without exceeding maximum airspeed limitations was difficult. The HUD could still be used during this phase of flight when used in concert with HDD instruments. All other maneuvers were satisfactorily flown by reference to the HUD.

Electromagnetic compatibility. All aircraft electrical and electromechanical systems were observed while power to the HUD was cycled. Test results showed no interference problems. Several systems were activated and deactivated in-flight with the HUD operating to evaluate aircraft systems compatibility with the HUD. Test results indicated that the HUD and aircraft instruments were compatible.

HUD warning repeater. The master caution repeater on the HUD display was verified by switching off each engine-driven generator in turn. Master caution annunciation in the HUD FOV was determined to be extremely valuable in alerting the pilot to check other cockpit indications outside the HUD FOV.

Pilot Interface Tests

The HUD display was evaluated under a variety of conditions to demonstrate that the controls, modes, and display were usable under normal flight conditions. In some cases, these evaluations were combined with instrument approaches. The basic flight symbology shown in Fig. 1 was the symbology set evaluated during certification flight tests. The compressed pitch scale, counterpointer air data displays, and heading tape were used on other HUD development programs with success.[6] Navigation and instrument approach data were available for display in the HUD FOV. Command carets were also available for setting desired heading, airspeed, and altitude. A decluttered display option was also evaluated to determine the effectiveness of decluttering the display during unusual attitude recovery. Although attitude, airspeed, and altitude data were presented in the conventional T format, heading and bank pointer data were not conventionally displayed. A ground bank pointer was used instead of the head-down sky bank pointer. Additionally, aircraft heading was also displayed on a tape display at the top of the HUD FOV. None of the evaluation pilots found these unconventional data displays objectionable. The symbology set was changed after certification to bring the display format in concert with HDD indicators. The ground pointer was changed to a sky pointer, and the heading display was changed to a 60-deg compass rose at the bottom of the HUD FOV. Additionally, airspeed and altitude displays were changed to vertical tapes instead of the counterpointer displays. This was done at the request of customers that were accustomed to similar displays found in some electronic flight displays.

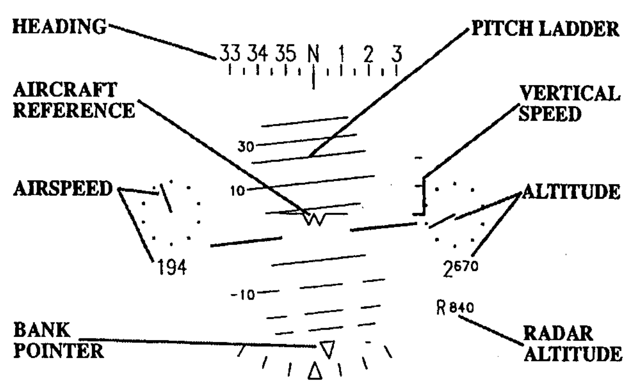

Fig. 1 Basic flight symbology.

Readability. The readability of the display was evaluated during day, dawn, dusk, and night flights. The brightness range was adequate. The HUD symbology was bright enough to view when the sun was in the FOV, although the display was uncomfortable to use. The brightness range at night was adequate, although the symbology occasionally became lost in the city lights. It could be made visible, but no single brightness level worked for the airplane reference symbol and the side scales. If the side scales were adequately bright to see, the runway was obscured. If the brightness was low enough to view the runway, the side scales were not perceptible. During dusk, the ambient brightness changed, particularly with backlit clouds. This required frequent adjustments in brightness. Brightness control is a generic HUD problem and is usually managed by manually adjusting brightness during those occasions when atmospherics require it or through an autobrightness control found on more sophisticated systems. The evaluation also examined the HUD for optical deficiencies such as flicker, excessive brightness variation across the FOV, symbol distortion, distortion of real-world objects, legibility of symbols, secondary symbol images, reflections of real-world images and lights, visual disparity, and interference with view of real-world cues. Optical characteristics were satisfactory. There was a secondary image of the symbology that could be seen if the pilot's head was lowered 6–8 in. Lowering of the head to that distance, while attempting to look through the HUD FOV and fly the airplane, was not a natural movement that would occur during normal operation of the aircraft. The secondary image, therefore, was not considered a deficiency. Tests evaluated the HUD for unsatisfactory display dynamics such as jitter, excessive lead or lag, excessive noise, and mutual interference of symbols. There was some minor jitter barely discernible during some night and IMC operations. It was not annoying and did not interfere with HUD operation or aircraft control. The jitter was eventually corrected through a new release of operational software.

In-flight initialization. Ease of in-flight initialization was verified. During flight, the system was switched off and on again to force an initialization. The workload was low, as the HUD recovers to a smart condition, and requires no pilot intervention.

Engine failure. Simulated engine failures were accomplished by the safety pilot using throttle cuts. A zero-thrust throttle setting was used in place of propeller feathering. Zero thrust was set by the safety pilot following identification of the failed engine by the evaluation pilot. The vision restriction system was used for all tests. Results indicated that following an engine failure, continued flight by reference solely to the HUD was difficult during turning flight. The absence of sideslip information in the HUD FOV increased pilot workload. Additionally, changes in power settings during engine-out missed approaches increased workload excessively, particularly during turning flight. The AFMS prohibits the use of the HUD during single-engine flights.

Unusual attitude recognition and recovery. Unusual attitude recoveries were accomplished when the safety pilot maneuvered the airplane while the evaluation pilot looked away from the HUD and HDD instruments. The vision restriction system was in place during these evaluations. The results indicated that the recognition of an unusual attitude recovery could be accomplished if the upper and lower navigation areas of the HUD were deactivated, so that the entire pitch scale was visible. Recognition was hampered with the navigation areas active. A body of collective opinion in the HUD user and certification community suggests that attempting to recover from an unusual attitude using the HUD alone can be an unsafe practice. The reasons are numerous, controversial, and not well documented. Among the causes cited are display dynamics, symbology design, and human factors. The FAA chose to take a conservative approach until this HUD had established a service history, and the subject could again be revisited. For this reason, the AFMS was written to require cross-checking HDD instruments to confirm that the unusual attitude exists and then require recovery from the unusual attitude using HDD instruments. Prospective HUD customers voiced no objection to adding this restriction to the AFMS.

Sensor failure recognition. Sensor failures were simulated by pulling circuit breakers or by using flight test software designed to inject system failures through a laptop computer. Sensor failures were presented at unexpected times during the flights with emphasis on presentation during instrument approaches. The vision restriction system was in place during these evaluations. When the pilot recognized the failures, the system was restored and the maneuver task continued. Results indicated that critical failures were detected immediately. Flight director failures took longer to develop, but were detected before significant excursions from the flight path occurred. Secondary data such as distance measuring equipment (DME) and radar altitude were often missed for a long period since the pilot may not have been using the subject data at the time. The ADF failure was not obvious by looking at the HUD display. The indicator symbology did not disappear as with the other navigation sensors, but simply froze. The frozen indicator took a significant time to detect if the aural identifier was not monitored. The head-down instrument has the same problem. A conservative approach was once again taken and a caution to this effect was placed in the AFMS.

HUD modes and options. During all flights, the general utility of the HUD was evaluated. The HUD performed satisfactorily for the intended mission of a corporate aircraft. Two areas of deficiency were noted and corrected. The radar altitude digits remained active at all times, even above the maximum display altitude of 2500 ft. This resulted in misleading data being presented and was corrected in the final release of operational software. Additionally, below 2500 ft, the terminal digit showing units was in constant motion, and thereby distracting. Above 500 ft the display was changed to indicate to the nearest 10 ft. A placard indicating the action of the optics locking lever was required and was added to the design data.

Command carets and indicators. The command carets and indicators, used to set target airspeeds, altitudes, and headings on the HUD, functioned as intended.

Traffic detection. The HUD enhances the ability of the pilot to detect traffic during all phases of visual flight. No problems were indicated with detecting traffic. To the inexperienced HUD user, channelized attention in the HUD FOV is a common pitfall and can hinder traffic detection. The AFMS describes the cautions pilots must be aware of when using a HUD system. Some of these cautions are instructions on setting the display brightness, looking through the HUD in addition to looking at the symbology, keeping an effective scan of symbology of both HUD and HDD data, and resisting the tendency to stare at the HUD symbology.

Instrument Approaches

A total of 88 instrument approaches were flown with six evaluation pilots. Of the six pilots, four were FAA aircraft certification flight test pilots, one was a corporate pilot, and one was a general aviation pilot. Of the six, two had prior HUD experience in military aircraft. The HUD was found suitable for flying instrument approaches. In particular, pilots commented favorably that the HUD improved approach performance and enhanced situational awareness during night circling approaches.

Objective results. Valid recorded data were obtained on 53 approaches. The results are summarized in Table 1. The errors listed in Table 1 are rms errors. Lateral course errors, glide slope errors, and ADF bearing errors were measured while on final approach inside the final approach fix. Approach airspeed and course error can usually be interpreted as a measure of pilot workload. All approaches were graded successful by both the evaluator pilot and safety pilot. Approach performance ap-

Table 1 Instrument approach rms errors

Approach type	Airspeed error, KIAS[a]	Lateral error, dots	Glideslope error, dots	ADF angular deviation, deg
ILS with flight director	7.3	0.4	0.5	NA
ILS raw data	7.5	0.6	0.7	NA
VOR	6.8	0.5	NA	NA
ADF	6.9	NA	NA	5.3

[a]Root mean square error from V_{ref} = 120 kn.

peared to correlate well with performance attained using HDD instruments.

Subjective results. Valid data were obtained on 88 approaches. Pilots rated the overall readability, controllability using the HUD, and the orientation readability during course interception. All approaches received satisfactory ratings in terms of readability and controllability. Engine-out and ADF approaches were rated poorer than all others in terms of readability and controllability. Evaluation pilots were more critical of their performance than the safety pilots who were observing the approaches. Instrument approaches are generally considered high workload tasks, and as such, a workload issue surfaced during this portion of the evaluation. The HUD was not integrated with systems such as the flight director course and heading markers, altitude alerter, and airspeed set markers. As a result, when flying an ILS approach with the flight director engaged, course and heading bugs had to be set on both the HUD and HDD instruments. The resulting workload was high and led to confusion throughout the approach. The final version of operational software was changed to remove the HUD course and heading markers any time a flight director mode was engaged. The flight director steering references could still be monitored by cross-checking the HDD instruments. During raw data approaches, the HUD course and heading command carets were available and enhanced approach performance. The AFMS was written to emphasize the advantages in setting up approach and navigation aids early in the approach sequence.

Operational Tests

Following formal flight testing, a separate function and reliability test was conducted. The purpose of this test was to evaluate the HUD in operationally representative flight environments. Twenty h in a representative environment were required. Twenty-four flights totaling 28 h yielded 20 h of creditable operational testing. The representative conditions included high-density airports and airspace, uncontrolled airports, and a broad spectrum of weather. Both single-pilot and two-pilot operations were conducted. The evaluation pilots were qualified in the aircraft. One FAA flight test pilot and two company operational pilots participated in the operational test program. A safety pilot familiar with the test program occupied the right seat and completed observation cards. For single-pilot flights, the safety pilot did not handle any cockpit or communications tasks.

In general, the evaluation pilots found the HUD presented them with useful cues that assisted in the conduct of the flights. Two items were noted. During one flight, a sloping cloud formation presented strongly compelling false horizon cues. The pilot flew HDD for a brief period of time. The AFMS cautions the pilot about atmospheric phenomena that may be disorienting. During flights into a rising or setting sun, the visual discomfort of trying to view the HUD with the sun in the FOV also made use of the HUD uncomfortable.

AFMS Evaluation

During all tests, a concurrent evaluation of the adequacy of the AFMS was made. Evaluation pilots were asked to comment on the suitability of the material. As a result of the engine failure tests, a restriction on flying by reference to the HUD with an engine out was placed in the flight manual supplement. As a result of the unusual attitude recovery tests, a caution note regarding cross-checking with head-down instruments was added. As a result of the sensor failure tests, a caution note regarding ADF flight was included. The description of the ILS symbology was not clear to some pilots. This section was rewritten. Because of the likelihood of presenting invalid data, the flight manual supplement prohibits the use of the HUD in any conditions with the maintenance computer terminal connected.

Discussion

The subject HUD was found suitable for operation during all phases of flight. A multiple supplemental type certificate was issued. The AFMS approved with the supplemental type certificate required that the HUD be used in IMC conditions only when an appropriately rated pilot occupied the right seat. The findings detailed next required correction for the two-pilot IMC operation restriction to be removed.

Symbology

1) Improved discrimination of the vertical velocity indicator (VVI) zero reference was required. The zero rate of climb index was easily obscured. The applicant provided a double-stroke video line for the zero reference.

2) Improved discrimination of the on glide path reference mark was required. The on glide path reference mark was double stroked to provide better discrimination.

3) The proximity of the digital altitude and the radar altitude displays was considered to be too close. The closeness of the two displays in the HUD FOV provided a potential for confusion. The radar altitude display was not moved, but the size of the digits was rescaled to provide better discrimination from the barometric altitude digital display.

4) The radar altitude display at altitudes greater than 1000 ft above ground level needed to be removed. The applicant removed the radar altitude display at radar altitudes greater than 1000 ft above ground level.

Human Factors

Results of the certification flight test indicated that unusual attitude recovery may be hampered when the navigation areas are displayed during recognition and recovery. An automated declutter mode was required to facilitate unusual attitude recovery. The bank and pitch limits at which the display declutters should be related to the type and sensitivity of unusual attitudes likely to be encountered in the aircraft in which the system is installed. The HUD symbology was set to automatically declutter at 20 deg positive pitch, 15 deg negative pitch, or 45 deg of bank. The normal display returned when normal flight parameters were regained for a predetermined period. Additionally, a manual declutter switch was provided on the pilot yoke to provide the declutter function whenever desired.

Follow on Tests

The proposed changes addressing these findings, after engineering review, were evaluated by flight test personnel using appropriate portions of the type inspection authorization used to originally certify the system. All changes were found satisfactory and the supplemental type certificate was amended to delete the multiple-pilot requirement for flight in IMC.

HUD Evolution Since Certification

Subsequent to certification, the subject HUD has undergone a series of modifications to reflect both customer desires and emerging regulatory guidance. As described earlier, the display symbology was modified to change the altitude and airspeed data to a tape format. Heading and bank pointer displays were changed to follow the basic T format. A conformal pitch attitude display was also developed for use in aircraft equipped with an inertial reference system. A turn and slip display was added by displaying output from a yaw rate gyro. The FAA Transport Aircraft Directorate categorized the HUD as a primary flight display when installed in transport category aircraft. As such, regulatory guidance relating to primary electronic flight displays has been applied to the HUD system. Currently, each HUD installation is considered unique, and a certification basis specific to the particular installation is developed for each program. The FAA is currently developing generic guidance that would apply to all HUD installations in fixed wing aircraft.

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