Flight Test Procedures

Now it is time for flight tests to determine the required parameters for a given airplane in a given configuration. Here is one possible scenario:

1) Do glide tests (knowing the best glide angle, and the speed for it, for given W and σ is sufficient). This gives C_{D0} and e, which in turn gives G and H. A reviewer accurately pointed out that getting drag polar parameters from glide tests is a tricky business; a windmilling propeller produces extra drag, stable air is required, and nonstandard temperature lapse rates must be accounted for. It would be best to use the zero-thrust apparatus and careful techniques pioneered by Norris and Bauer.[3]

2) Do best angle of climb tests for V_x. Since we know H, this gives us $K = (F - G)$. Since we know G, this gives us F, which gives us the propeller polar intercept b. The required inversion is

$$b = \frac{SC_{D0}}{2d^2} - \frac{2W^2}{\rho^2 d^2 S\pi eAV_x^4} \tag{18}$$

For an intuitively correct power drop factor, b will be negative.

3) Do either maximum level flight speed tests for V_m or best rate of climb tests for V_y. Since we have H and K, either will give us E, which will give us propeller polar slope m. Using an experimental V_m,

$$m = \frac{2n_0 dW^2}{\phi(\sigma)P_0\rho S\pi eA}\left(\frac{1}{V_m^2} + \frac{V_m^2}{V_x^4}\right) \tag{19}$$

while using an experimental V_y,

$$m = \frac{2n_0 dW^2}{\phi(\sigma)P_0\rho S\pi eA}\left(\frac{3V_y^2}{V_x^4} - \frac{1}{V_y^2}\right) \tag{20}$$

Once these three tests (plus POH information) complete our knowledge of the 11 numbers, we can find any or all of the three V speeds (or P_{av}, P_{re}, thrust, drag, or anything that depends on any of these) for any desired values of gross weight and atmospheric density (or density altitude).

Conclusions

This analysis allows realistic flight performance prediction without propeller charts; those are often hard to get and, even if available, need to be corrected for fuselage profile. The technique is remarkably fertile, needing little time to make graphs showing density altitude and weight dependencies of each of V_m, V_y, and V_x; P_{av} and P_{re} curves; rates and angles of climb for various speeds, weights, and altitudes; the same for sink rates; the speed dependence of parasite, induced and total drag force; and absolute ceilings, and speed there, for a given weight.

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Flight Testing a General Aviation Head-Up Display

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Introduction

THE head-up display (HUD) was originally developed for military aircraft from reflecting optical sights. The HUD places flight and navigation data in the pilot's forward field of view (FOV). This data symbology is presented as a collimated image that appears to be floating at infinity. A semitransparent mirror (the combiner) allows the pilot to view the symbols simultaneously with the real world.

A typical HUD presents the information from the basic T instruments: airspeed, altitude, pitch and roll attitude, and heading. In addition, appropriate course (and glide slope) deviation data can be selected for display. Distance measuring equipment (DME), flight director, radar altitude, and marker beacon passage can be shown if available.

The HUD can also be used to display other information, such as master warning/caution information, an electronic checklist, and a stopwatch timer.

Aircraft Constraints

The FV-2000 HUD was developed as a low-cost display for retrofit into executive and corporate aircraft. Several constraints became apparent at the outset. The space available in the candidate airframes limited the combiner size. The resultant FOV is rather small, approximately 9 deg.

To minimize cost, the FV-2000 differs from most military and transport HUDs in that it uses conventional aircraft gyros rather than an inertial platform for attitude information. This created a potential problem since the aircraft gyros are less accurate than inertial platforms.

The small FOV and the potential difficulty in providing accurate registration led to a decision not to insist on conformality with the external visual scene. To minimize any subjective discomfort, the HUD symbology is compressed relative to the real world. This has the added benefit of enhancing pilot spatial orientation. The remaining design issues dealt with cockpit integration: always a problem when retrofitting a digital display into an existing analog cockpit.

HUD Criteria

There are no criteria for head-up displays in the civil community. In fact, at the time, there were no agreed upon criteria for HUDs in any community, civil or military. Criteria had to be developed for the King Air installation.

Generally, existing guidelines were used to the extent possible. Advisory Circular 25-11 (Ref. 1) was used for many of

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the electronic display issues, although it does not deal with many HUD-specific issues.

The model FV-2000 HUD is intended for use as a supplemental display. The aircraft will still require the full complement of conventional panel instruments required by the appropriate operating rules. For this reason, the system reliability concentrated, ensuring the integrity of the displayed information.

Certification Basis

The significant certification rules dealing with the certification of aircraft systems are FAR 23.1309 (Ref. 2) for normal category airplanes or FAR 25.1309 (Ref. 3) for transport category airplanes. The requirements for transport category airplanes are generally more stringent than for normal category. Choosing a normal category airplane was thought to minimize certification risk (i.e., schedule risk) for the initial installation.

The Beech King Air series was chosen for the initial installation. These represent the largest group of corporate airplanes and are certified to FAR 23 or its predecessor CAR 3. All King Airs have the same cockpit structure, minimizing differences between the various models.

The application for the supplemental-type certificate specified amendment 23-40 of FAR 23 as the certification basis. This ensured that all models of King Airs would be covered. As matters developed, the certification basis became the subject of an issue paper. The Federal Aviation Administration (FAA) felt that HUDs were not covered by the original certification rules and that the current version of FAR 23 should be used. Amendment 23-41 became effective during the interval between the preparation of the application and its submission to the FAA. As a result, amendment 23-41 was the certification basis for the installation.

Amendment 23-41 largely eliminated the distinction between normal and transport category airplanes for systems certification.

Initial Development

A symbology development program was established using a single-engine Grumman AA-5, perhaps the only general aviation single-engine airplane with a HUD and an air-data computer. A programmable symbol generator was installed allowing in-flight changes to the HUD symbology. A laptop computer was connected to the HUD via a serial interface. The laptop was strapped in the rear seat and allowed the safety pilot to change individual symbols quickly.

To simulate IMC, a set of complimentary color filters was used, similar to those used in the CALSPAN NT-33 (Ref. 4). The windshield and canopy sides were covered with red transparent plastic sheet. The evaluation pilot wore a blue–green visor. This blocked the external scene but allowed view of the HUD symbology. The safety pilot could see the external scene although the colors appeared unnatural.

Symbology Development Flights

The symbology development program was designed to allow a choice between two candidate formats for airspeed and altitude scales (tapes vs counterpointers), two choices for heading scales (on horizon and a scale in the top of the FOV), and several choices for navigation presentation.

Seven evaluation pilots were used during the symbology development. Two were experienced test pilots and five were operational pilots (two with military experience and three with predominantly civil experience).

The pilots were assigned a flight task (instrument approaches, terminal maneuvering and navigation tasks, and unusual attitude recoveries). They were to rate their performance using a NASA/Army developed display rating scale.[5] The non-test pilot evaluators were talked through the logic tree by the safety pilot. The evaluators were also asked for their preferences. The pilot preferences did not correlate well with the display ratings.

Objective performance was recorded on rating cards completed by the safety pilot. No other data recording was used.

Scaling Development

Optimal pitch scale compression was determined solely by the Flight Visions project pilot (RLN) in the Grumman. The flight tasks were instrument approaches and unusual attitude recoveries. Control pulses (particularly in pitch) were used in addition to define acceptable pitch scale compression. The criteria used was the minimum compression allowing ease in recovery from unusual attitudes without creating adverse problems during instrument approaches. Only display ratings were used during these flights.

Flight director scaling was based on workload during instrument landing system (ILS) approaches. These evaluations were performed in the King Air by the project pilot. Only display ratings were used during these flights.

Certification Flight Tests

Flight Test Issues

Several flight test issues were raised during the initial discussion with the FAA.

The HUD was intended as a supplemental display, not as a replacement for the panel instruments. Flight procedures were developed to require the pilot to include the head-down instruments as part of his scan. Most of the flight tests allowed the evaluating pilot to utilize both the panel instruments and the HUD. When insufficient cues were not available on the HUD, the pilot was directed to use the panel instruments and announce this action to the safety pilot.

A major issue during the development was the need to annunciate data failures. As the design developed, most symbols were simply removed if the data was detected to be bad. Some symbols did have specific warnings if the source data failed. These were those that were critical (attitude failure) or that were considered to be difficult to detect (compass or glide slope failure).

The procedure was to simulate invalid data by injecting failures into the HUD computer and determine how long the pilot took to detect the failure and announce that he was reverting to panel instruments. Failures introduced included attitude gyro, compass, airspeed, altimeter, and one- and two-axis flight director soft-overs. Automatic direction finder (ADF), DME, and glideslope failures were induced by pulling the appropriate circuit breaker.

A concern was expressed that the HUD symbology might interfere with the pilot's view of other aircraft. The pilot flying with the HUD was instructed to announce traffic verbally. The safety pilot, assigned to watch for traffic, was to record which pilot saw the traffic first. Obviously, this test was not performed when the complementary color filters were in use.

A concern was expressed that the HUD system might increase pilot workload excessively. All evaluating pilots are asked to evaluate their workload subjectively.

Calibration Flight Tests

The initial flight test sorties ensured that the HUD met all design criteria and had satisfactory navigation gains. The tasks were typical profiles specified by the Flight Test Guide.[6] These tasks included evaluating VHP omni range (VOR) accuracy, VOR/ILS tracking, and station passage.

Basic Suitability of HUD

The first set of tasks were to be flown solely by reference to the HUD. They were designed to ensure that the HUD provided sufficient cues during dynamic maneuvers: full-flap instrument and visual approaches, go-around, steep turns, emergency descents, and single-engine operation. These aggressive tasks were primarily designed to ensure that the HUD's presentation, particularly the pitch compression, was suitable for flight. These tasks were to be flown solely by reference to the HUD.

Both day and night flights were included as were flights into and away from the sun during early morning and evening.

These initial tasks were flown by the project test pilots. The Flight Visions project pilot (RLN) flew these tasks during the company flight tests. The FAA project pilot (MWA) flew them during FAA flight tests.

For most tasks, the aircraft could be controlled solely by reference to the HUD. The exception was engine-out flight. In the absence of sideslip information on the HUD, yaw control could only be maintained in wings-level flight by applying sufficient rudder to hold a constant heading. In turning flight, yaw control was open-loop since no cues were available on the HUD.

Operational Suitability

These tests were flown to evaluate the overall suitability of the HUD when the pilot was allowed to use all available information. Tasks included basic maneuvering, engine-out flight, and failure detection. Each pilot also evaluated the basic workload and flew a series of instrument approaches.

Instrument approaches included ILS, localizer, back-course localizer, VOR, and ADF approaches. Both day and night circling approaches were flown. Approximately 80 approaches were documented. One approach in 10 was flown with a simulated engine failure. Tracking data was recorded during these approaches. During these approaches, a flight test engineer introduced unexpected systems failures to determine the ability of the pilot to detect these failures.

These tasks were flown by several pilots. The company flights were flown by four pilots: three nominated by Flight Visions and one by the FAA. FAA flights were flown by three FAA pilots. Flight Visions elected not to nominate one pilot for these flights.

Operational Evaluation

Twenty-five hours of representative corporate missions were flown using qualified King Air pilots, including flights into primary TCA airports, day flights, VFR and IFR flights, and single-pilot flights.

Results

Initial Development

The single-engine Grumman provided an inexpensive screening tool to develop HUD symbology. The major outcome of these flight tests was the choice of airspeed and altitude counterpointers over the original scale choice: vertical tapes.

Three sets of subjective data were obtained during these flights: 1) pilot preference, 2) display readability ratings, and 3) display flyability ratings. The preference data were inconclusive. Three pilots strongly preferred tapes, one was neutral, and two had a slight preference for counterpointers. It would be difficult to justify a choice based on this table, but the tendency would lean toward tapes. The three pilots preferring tapes all had extensive flight experience in aircraft equipped with tape displays.

The display ratings were more informative. The counterpointer ratings are all threes with one four for flyability. Clearly, counterpointers are acceptable.

The display ratings for vertical tapes showed a difference between airspeed and altitude scales. The airspeed ratings were slightly better than those for counterpointers. However, when we examine the data for altitude, the flyability ratings are quite different. Three pilots rated the display low because of difficulty in detecting slow deviations while attempting to maintain their assigned altitude. This did not reflect on their ability to read the display, only to use it for flying.

This was also borne out by the objective data. There were a significant number of instances with tapes where the pilot would drift slowly from his assigned altitude and abruptly return. This appeared to be caused by difficulty in detecting small rates and a lack of a fixed reference. This effect was not observed with counterpointers.

The final symbology is shown in Fig. 1.

Certification Tests

During the certification tests in the King Air two significant differences between the Grumman and King Air flights were observed.

The original HUD design incorporated a checklist function. This displayed the current checklist item written across the bottom of the FOV. A button on the control yoke advanced the checklist. During the early flights in the Grumman, the checklist was of minor concern. However, during the initial flights in the King Air, the workload increase was noticeable, but not intolerable. As instrument approaches began in earnest, the workload increased to the point that it was an annoyance.

Finally, when flights in a high traffic density airspace began, the collateral workload was unacceptable. The results forced the removal of the checklist function prior to FAA flights.

The second difficulty was the lack of cockpit integration. This is not a fault of the HUD, but is rather caused by the avionics suite already present in the King Air. The particular installation required multiple reference inputs to make use of the various alerts and reminders. Two separate altitude alert values had to be set: 1) two separate heading bugs and 2) an airspeed reference caret. This was exacerbated by the need to keep one's head in the HUD eyebox.

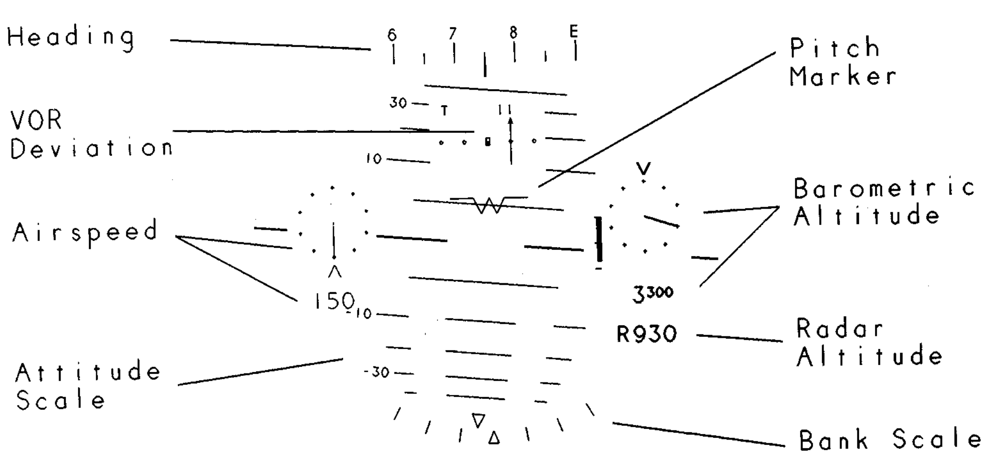

Fig. 1 HUD symbology.

Failure Detection

In spite of preflight test concerns, pilots readily detected all failures introduced during the flight tests with the sole exception of ADF failures, which resulted in frozen indicators, both head-up and head-down. This is a criticism of the ADF design, not the HUD.

Unusual Attitude Recoveries

Initial unusual attitude recoveries were performed with navigation data removed from the HUD. The HUD ratings were generally threes. During FAA flights, the pilots flew the unusual attitudes with navigation data shown. The added clutter and conflicting rotational cues caused the ratings to deteriorate to the seven or eight level. As a result, the HUD was modified to provide for automatic declutter during unusual attitudes. A yoke-mounted declutter button was also added.

ILS Symbology

Maintaining geographical orientation appears to be more difficult with a HUD than with a head-down display. The ILS symbology used a small cross to show raw deviation and a single cue airplane to show flight director commands. Some pilots reported difficulty with the raw data symbol, confusing it with split cue flight director needles.

Choice of Pilots

The combination of test pilots and several operational pilots worked well. Generally, the two groups agreed on relative ratings. However, operational pilots tended to rate the display readability and handling one or two rating points better than the test pilots.

Lessons Learned

Use of Surrogate Aircraft

The single-engine Grumman allowed an inexpensive screening tool to develop HUD symbology.

Effect of Workload

At the same time, care must be taken when using a surrogate aircraft. We recognized that initial King Air flights would need to check the dynamic response of the HUD to ensure satisfactory handling using the HUD, but did not recognize that the increased workload would be so dramatic for HUD functions such as using the checklist.

The effect of workload caused by high-density air traffic was not anticipated. Future display evaluations should ensure that representative ATC workload is present and not perform evaluations in a sterile environment.

Test Pilots vs Operational Pilots

The combination of two test pilots with two to four operational pilots seems to give a suitable combination of critical evaluation and a variety of pilot background.

Unusual Attitudes

The original flight tests tasked the pilots with recovering from unusual attitudes with decluttered HUDs. When the test was repeated with navigation data shown, the HUDs were significantly downrated. Future HUD flight tests should conduct unusual attitude recoveries with maximum symbol density (i.e., minimum declutter).

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Integrated Digital Avionics to Improve Aircraft Environmental Control Systems

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Introduction

INTEGRATED digital avionics technology has been an innovation of tremendous importance to aircraft design and operations. The primary application of avionics traditionally has been in the areas of missions systems, crew stations, and flight controls. More recently, aircraft utilities including environmental control, fuel, hydraulics, and electrical power have also been interfaced with digital avionics.

There are several benefits that result from interfacing these utility systems with a digital avionics system.

1) Dedicated controls and displays can be replaced by multifunction controls and displays. The elimination of these dedicated components decreases weight and costs and increases reliability.

2) Automating the routine operation of utility systems improves operational effectiveness and safety by lowering operator workload.

3) Built-in test (BIT) and failure recording simplify maintenance.

4) Systems that are digitally interfaced can share data. Through the use of this shared data redundant measurements can be reduced with consequent decreases in weight and costs.

5) Mission reliability can be increased by dynamic reconfigurations that retain mission capabilities, even with hardware failures.

The V-22 Osprey is a tiltrotor aircraft being developed by the team of Bell Helicopter Textron and The Boeing Co. It features a digital avionics architecture that integrates all of the systems of the vehicle. The environmental control system (ECS) of the V-22 provides several examples of the benefits of integrating utility systems with digital avionics.

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