Flight Director Design for a STOL Aircraft

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All weather capabilities for aircraft depend heavily upon precision guidance during the landing-approach maneuver, particularly in turbulent, low visibility conditions. Whether or not this type of maneuver can be accomplished by a pilot in zero-zero conditions by reference to instruments alone, with the consistent accuracy required, is a subject of some debate. The advantages of a reliable manual landing system (as opposed to a fully automatic system) are referenced. However, a recent FAA study has concluded that present day flight director systems do not allow pilots to demonstrate accuracy comparable to automatic systems. The study described here was intended to explore some ways of giving the pilot the information necessary to perform as well as an autopilot. A fixed-base flight simulator was built to study pilot/director/aircraft performance. Instrument rated pilots used the different director-displays in an approach down to touchdown, including a flare and decrab maneuver. Two well established areas of control theory are combined in the design of the cockpit display. Optimal control theory and the theory of manual control are used to find the feedback gains required to drive the display symbols. Conclusions based on the simulator are presented. The results show that the director display developed in the work provides more than adequate information for simulated landing in highly turbulent conditions. Comparisons between a full control director and a director which allowed the pilot some latitude in decision for control moves indicated that the latter approach is feasible with minimal training and much preferred by the pilots.

Nomenclature

F = optimal control feedback matrix
IP = performance index
K_a = roll rate to aileron input gain
K_b = display gain in pitch axis
K_d = display gain in roll axis
K_p = pilot gain
G_p = pilot transfer function (used in pitch axis control case)
q_i = element weighting ith output in IP
r_i = element weighting ith control in IP
$\bar{X}$ = state vector, made up of the state variables: normal velocity, pitch angle, pitch rate, airspeed, vertical beam deviation, side velocity, roll angle, roll rate, yaw angle, yaw rate, lateral beam deviation
$\bar{Y}$ = output vector
$\bar{U}$ = control vector, made up of: throttle, elevator, aileron, rudder
$\delta_e'\ \delta_e^*$ = elevator deflection; the asterisk indicates the "optimal" value for these variables
$\delta_a'\ \delta_a^*$ = aileron deflection
$\delta_r'\ \delta_r^*$ = rudder deflection
θ = pitch angle
θ_c = commanded pitch angle
ϕ = roll angle
ϕ_c = commanded roll angle

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Introduction

WITH the move to improve the air traffic situation in this country by lowering weather minimums for routine operations, much attention is being given to precision guidance, including the design of flight directors. Since past performance has indicated some lack of precision attainable with currently available instruments,[1] studies have been directed toward the design of appropriate feedback systems to drive the symbols of the display. Experimental methods were used by Naish and Von Wieser,[2] who give arguments supporting manual systems. Frequency response methods were used in an analytic study of flight director design by Weir, et al.[3] This report deals with a method which uses an analytic (and computer) method to find over-all feedback gains and an experimental procedure to find a good display gain for each axis of control. The advantage offered is that the computer design method used is very quick (although a digital computer is required) and is based directly upon system response, which winds up being the final criteria for all design procedures. Once the feedback gains are found, experimental design is minimal since only one gain, the display gain, needs to be optimized experimentally. The method has been applied to a representative STOL aircraft as part of a NASA sponsored STOL transportation project at Purdue University, but is applicable to any type of aircraft, in a broad class of maneuvers.

The Aircraft

The aircraft used as a model in this work was the Breguet 941, Fig. 1. A more complete description can be found in Refs. 4 and 5. Briefly, it is a French-designed, 64 passenger short-takeoff-landing (STOL) aircraft which has been evalulated in the U.S. by Eastern and American Airlines in the short-haul, commuter type of service. The turboprop driven aircraft is characterized by a steep glide path angle (7½°) and a slow approach airspeed (60 knots). Typical landing distance over a 50-ft obstacle is

Fig. 1 Breguet 941 aircraft.

less than 1000 ft. The handling qualities of the Brequet are rated acceptable with some slightly disturbing lateral characteristics which are typical of STOL's. The phugoid period is about 35 sec with low damping and the short period oscillation is well damped with a period of about 15 sec. The directional oscillation has an 8-sec period with a damping ratio of about 0.1. Since the Breguet is a blown wing aircraft, airspeed is not considered a primary variable and is replaced by angle of attack (0–3°) and throttle to maintain the desired sink rate in the landing-approach.[4]

Control

The control situation in the landing-approach can be considered as an infinite time, output regulator linear optimal control problem whose solution has been developed by Kalman[6] and is described in many control texts.[7,8] The four outputs selected to be controlled are vertical and lateral deviations from an ILS beam (with no noise), sideslip and airspeed.

Two sets of state equations (the equations of motion were assumed uncoupled) were formulated for the Breguet from stability derivatives found in Ref. 4, 9 and 10, one set each for the longitudinal and lateral modes. We obviously want to control the horizontal and vertical deviations from the ILS beam, but since we have four control inputs (elevator, throttle, aileron and rudder) we can control the steady state values of two more variables. Sideslip and airspeed were chosen based on experimentation with other variables in the digital design work. The performance index has the form

$$IP = \int_0^\infty \left(\sum_{i=1}^{4} q_i y_i^2 + \sum_{j=1}^{4} r_j u_j^2\right) dt$$

where the q_i's and r_j's must satisfy $q_i \geq 0$, $r_j > 0$ and the y_i's are outputs and u_j's are inputs. In this work a matrix exponential type of digital simulation was used to evaluate a particular controller design, based on the closed loop system response to initial beam deviations and steady winds with assumed values for the q's and r's. The responses were checked for such things as excessive sideslip, margin from the stall, pitch, roll and yaw excursions, control deflections, and response time and damping of the beam capture.

Typically about twenty runs are required to find a suitable solution. A remote, on-line computer terminal was used and one solution could be completed in about 10–15 min, including looking at the previous solution, deciding on changes for the q's and r's, entering the changes, and running and printing out the new solution and its responses. There are other design techniques which could be used to find a suitable closed loop control including classical theories and modifications to the optimal control formulation. However, because of the small number of free parameters and the multiplicity of design constraints, a technique as described above with the designer actively engaged in the design iteration has great advantages.

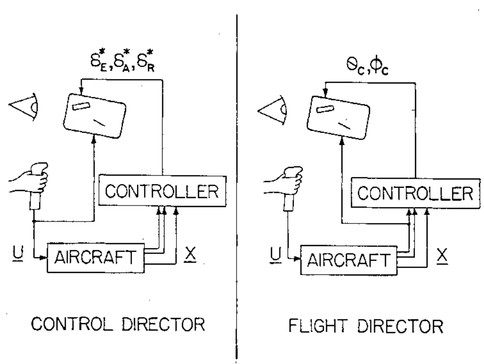

Fig. 2 Display format.

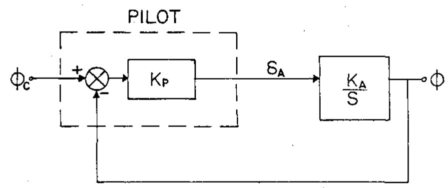

Fig. 3 Roll angle loop closure.

Display

Although the controller designed thus far is a closed loop type, we really want the system to be manual; that is, we want the pilot to close the loop. This means that we must display something which will cause the pilot to produce the control actions that the feedback controller has computed. One method of giving the pilot control commands is to tell him the desired pitch and roll angles that will return the aircraft to the beam after a disturbance. This is the present day flight director display. Another type of display, which could be called a control director, tells the pilot the actual and desired positions of the controls.

The same display symbols were used for both types of displays. The format is shown in Fig. 2. For the flight director the bar represents the aircraft attitude in pitch (vertical displacement of the bar) and roll (rotation of the bar). The lateral displacement of the bar indicates rudder pedal deflection. The box gives pitch, roll and rudder commands. For the control director the vertical displacement of the bar indicates elevator deflection and rotation indicates aileron deflection. The box then gives elevator, aileron and rudder commands.

The control director can be classified as a pursuit display (the output of the controlled element is displayed and the task is to get it to follow some command symbol) with no dynamics between the pilot and the controlled element (the controlled element in this case is the stick and the output is its position). Now if the pilot follows the commands given to him by the control director, we can consider the loop closed with a unity gain describing the pilot-display combination. The pilots neuromuscular lag

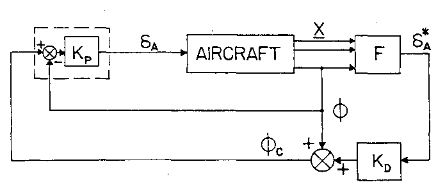

Fig. 4 Lateral control.

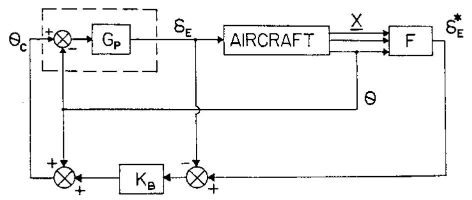

Fig. 5 Longitudinal control.

and time delay may be neglected when compared with the dynamics of the aircraft.

The design of the flight director requires the use of some results of the research in manual control.[11-14] We must now take into consideration the way in which the pilot will respond to pitch and roll commands. The goal here is to get the pilot to produce the same time history of his control movements as would have been produced by the optimal controller (keeping in mind that we do not want to ask him to produce an input which seems inconsistent with his senses). As an example of how to do this we will consider the lateral case of roll angle response to aileron input. To simplify matters we assume only aileron inputs to the aircraft. This is a good assumption since the Breguet pilot actually uses very little rudder, if any at all, in an ILS approach. The manual control situation can be considered a pursuit task for large maneuvers such as beam capture (the roll command is large and appears random to the pilot) and as a compensatory task for small corrections such as adjusting for wind gusts. The compensatory task consists of the pilot trying to zero the command symbol around the relatively stationary aircraft symbol. The aircraft symbol can be considered as a fixed reference and the command symbol as the output of the controlled element. Manual control theory tells us that the pilot will act as a simple gain, K_p, when he closes the loop around an element which resembles a pure integration. Roll angle response to an aileron input is approximately an integration in the frequency range 0–0.5 Rad/sec. This loop closure is shown in Fig. 3.

The over-all lateral control situation is shown in Fig. 4. The block labeled F is the state feedback controller which computes the optimal aileron deflection, δ_a^*. Now, since the pilot produces an aileron deflection

$$\delta_a = K_p(\phi_c - \phi)$$

we can find the necessary commanded roll angle ϕ_c, by rearranging this relationship and substituting δ_a^* for δ_a.

$$\phi_c = (1/K_p)\delta_a^* + \phi$$

This addition of roll angle to the roll angle command signal effectively nullifies the inherent feedback to the pilot of roll angle through the attitude indicator portion of the display. Now in the case where the beam has been captured and further roll motion is slight (i.e., the compensatory case) the pilot is again controlling an element which looks like a pure integrator in the lower frequency range. The controlled element is now the combined aircraft/state-feedback system whose input is aileron and whose output is commanded roll angle.

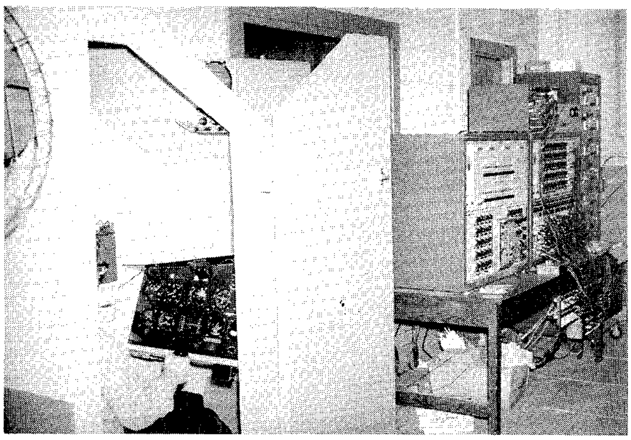

Fig. 6 Flight simulator.

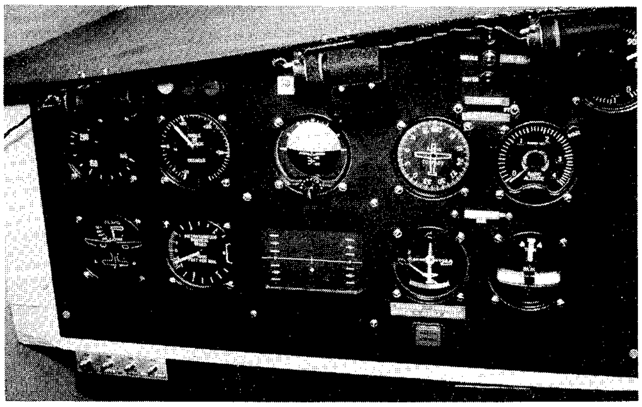

Fig. 7 Cockpit instrument panel.

In the pursuit task the pilot will adjust his gain such that the over-all system (from commanded roll angle to actual roll angle) has a unity gain over a broad bandwidth (0–10 rad/sec). During this time the display gain is relatively unimportant, compared to the time during which the pilot adopts the compensatory behavior, e.g., tracking after the beam capture. The problem now becomes the adjustment of K_d, the display gain on aileron, to account for the pilot gain, K_p, during the compensatory portion of the approach. If we can make K_d equal to $1/K_p$ then the loop will be closed with unity gain. But K_p will in fact depend on the value of K_d. The method used here has been to estimate the order of magnitude of K_p from a step roll command response and set K_d equal to one over this value. K_d is then adjusted experimentally to minimize the rms tracking error in the simulated approach.

For the pitch command we have the same type of situation after beam capture (and also during large disturbances and during the flare maneuver) the pilot is controlling an element (pitch attitude of the aircraft in response to elevator input) which looks like a double integration. This requires him to generate some lead compensation in pursuing the commanded pitch angle. A combination of the two previously described displays was used to capitalize on the good points of each. The longitudinal control situation is shown in Fig. 5. This type of display would be classified as pursuit with no dynamics in the controlled element (in this case the controlled element is the elevator, just as with the control director display).

Experimental Results

A fixed-base simulator was built to study the different types of displays. An analog computer simulation of the

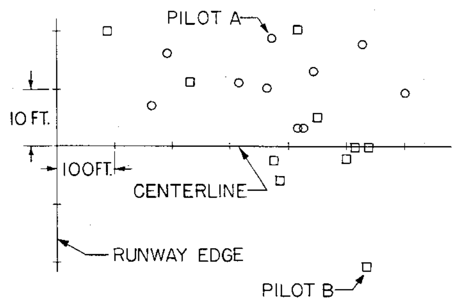

Fig. 8 Automatic and manual longitudinal beam capture.

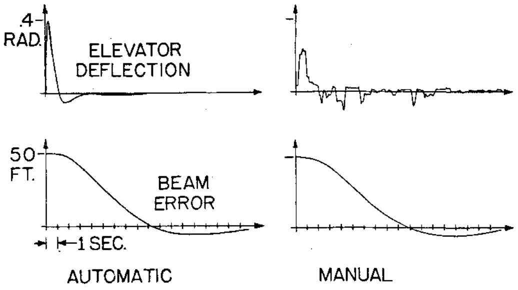

Fig. 9 Touchdown dispersion.

equations of motion drives the instruments in the cockpit mockup, shown in Fig. 6. The instrumentation consists of angle-of-attack indicator, instantaneous vertical speed indicator, attitude indicator, heading indicator, radar altitude, raw ILS indicator and a CRT display, Fig. 7. In addition to stick, rudder and throttle controls (which were matched to the characteristics of the Breguet controls) there are selector switches for autothrottle, yaw damper, roll damper, autocoupler and glideslope, localizer and altimeter sensitivity ranges. Marker beacon, stall indicator and status indicators are also provided.

The atmospheric environment simulated consisted of crosswinds of 15 knots, headwinds of 25 knots, tailwinds of 10 knots, wind shears up to 15 knots/100 ft and moderate turbulence of 6.5 fps longitudinally, 4 fps laterally and 2.5 fps vertically. These values correspond to standards recommended for CAT II automatic landing systems by the FAA.[15]

All together some 500 approaches were run in different portions of the testing. Two hundred of these approaches were completed with a flare, decrab and touchdown. Two instrument rated flight instructors with military flying experience were used as subjects in the bulk of the approaches flown to touchdown.

The control director did not afford the pilot any greater precision in the landing-approach task and was abandoned after preliminary tests. It was thought originally that if the control director could give the pilot more precise and direct commands, better control would be achieved and the transitioning between the control director and the attitude indicator (which the pilot inevitably refers to quite often) could be tolerated. In the experimental work it was found that even unbiased (nonpilots) subjects could do no better with the control director than with the flight director. The control director was, however, much easier for the nonpilots to learn, taking only about 10–15 min in contrast to 1–2 hr for the flight director to achieve a constant performance level, as measured by rms tracking error. The pilots, on the other hand, learned to use both displays in about the same amount of time but prefered the flight director because of the transitioning problem. Part of this preference can be attributed to habit but since no improvement was obtained with the control director, there is, at present, no reason to pursue its development.

In the final configuration the roll command and modified pitch command type of flight director was used. The autothrottle and roll damper were used to reduce pilot work load. A comparison of automatic and manual beam capture in the vertical case is shown in Fig. 8. The rms tracking accuracy was on the order of 6 ft laterally and 4 ft vertically. The approaches which were continued through the flare were stopped at touchdown and all variables recorded. Lateral dispersions were around 5–8 ft and longitudinal dispersions were about 140 ft (1 sigma values). A typical touchdown dispersion for one set of 20 landings is shown in Fig. 9. These values are comparable to touchdown distributions obtained in FAA tests with the Breguet at NAFEC.[16] The lateral dispersions seem to indicate the feasibility of operating with the 100-ft wide runways proposed for STOL ports but the longitudinal dispersions indicate either further work on the flare control or a longer runway than is presently proposed.

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