teria and will vary according to the kind of airplane being designed and the mission assigned. Only an intensive interdisciplinary effort will yield maximum benefits.

Building airplanes using modern control system concepts as previously discussed, requires significant improvement in flight control reliability. The reliability required is expected to advance to meet the need as industry recognizes the performance to be gained by the approach. To date, however, lack of flight-verified systems has precluded acceptance of these advanced concepts. Only a vigorous developmental effort, leading to flight test demonstrations, can give the aircraft designer the confidence he needs to apply these ideas.

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Pilot and Aircraft Augmentation on the C-5

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The C-5 military transport is typical of the new generation of transports. The gross weight, large pitch, yaw inertia, and low landing speed present new problems. These problem areas are alleviated by an augmentation system, designed to improve the handling qualities of the C-5. The C-5 pilots were able to log more than 500 hr on a simulator before the first flight. This simulator was a valuable assist in the analysis and design of the augmentation systems.

Introduction

THE pilots who flew the giant C-5 on its first series of test flights were not surprised when they found it a pleasant aircraft to fly because they had already flown it 500 hr on a C-5 simulator. Described in this article are some of the approaches (both simulation and actual) used in testing a modern transport, in this case the C-5. Also discussed is the major role augmentation plays in improving the handling qualities of large aircraft.

Built by Lockheed-Georgia (with a triple-redundant augmentation system provided by Honeywell), the C-5 is typical of the new transports in which the mass has been concentrated in the fuselage to accommodate the payload. Intended for long hauls, large loads and improved economy, it has a maximum gross weight of 764,500 lb and can carry a payload of over 100 tons. Cruising at 440 knots, it has a range of up to 6000 miles, depending on the payload. Because it must be able to land on short unimproved fields, the C-5 has high lift, flaps, slats, and a low landing speed. In addition, it has a landing gear with 28 wheels, four of which are on the nose gear and six on each of the four main bogies.

C-5 Characteristics

The C-5 is representative of a new class of aircraft in which the mass concentration causes the yaw and pitch inertia to be over six times the inertia for a conventional transport. This increased inertia requires large surfaces to provide the necessary control power and handling qualities at low speed. With the very low approach speeds, the aerodynamic forces are small and the control effectiveness is reduced. The static directional stability is also reduced at low speeds so that the turn coordination is poor. Many aircraft exhibit poor coordination at low speeds, but in this case the difference in yaw inertia tends to aggravate the problem.

The increased pitch inertia in the pitch axis contributes to a lower pitch frequency and thus the requirement for pitch rate feedback in the pitch augmentation. The C-5 has rather high short-period damping ratios but the short-period frequency is close to the phugoid (long-period motion). As a consequence, the two frequencies interact and what starts out as a short-period response ends up after a few seconds in a phugoid oscillation. This phugoid is easy to control but is disconcerting to the pilot in that it gives him the impression that the aircraft is hard to trim, or that it is wandering about about a trim point. This phugoid action is also present, to a certain extent, on the glide path approach where the pilot prefers a more positive pitch response.

Preliminary Analysis

Several agencies, including NASA Ames, Cornell Labs., and the research group at Wright-Patterson have conducted studies on these problem areas. Flight test and simulator studies have been used to predict the handling qualities of large aircraft at low landing speeds (Refs. 1 and 2). These studies predicted that with proper augmentation the handling qualities would be satisfactory at the low approach speeds. Their predictions on the need for improvement in Dutch-roll damping, turn coordination, and spiral stability were very worthwhile. The importance of flight path response, the need for new handling qualities criteria, and the importance of the phugoid motion were verified on a C-5 simulator and flight test studies.

Using this simulator, augmentation configurations were evaluated early in the C-5 autopilot design. This cockpit simulator, in conjunction with analog and digital computers, video display, and audio simulation, provided a more realistic evaluation of the system. The cockpit was free to move in pitch and roll with additional motion to simulate the contact with the runway. The moving belt camera and the video display in the cockpit gave a visual display of the terrain. Either a 3-degree-of-freedom or a 6-degree-of-freedom simulation was used depending on the nature of the problem. As the pilot commanded new attitudes or throttle settings, the computers provided the proper aerodynamic effects, instrument readings and change in display. Various augmentation configurations were flown on the simulator to obtain pilot comments and evaluate system operation. A typical simulation is described in the following paragraphs.

For a takeoff weight of 450,000 lb and a center of gravity at 29%, flaps extended, the pilot trims the stabilizer for climb. The throttles are advanced to 100% normal rated thrust, and, as the airplane accelerates down the runway, the nose gear is used to steer to the centerline of the runway. At 90

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knots, the rotation is started with acceleration to the V_2 climb speed of 112 knots at a climb angle of about 18° to 1500 ft. The video presentation is lost at 200 ft when entering the cloud base. At 1500 ft, the power is reduced to about 45% normal rated thrust, there is a pushover to level flight, and the aircraft is retrimmed.

During level flight, inputs such as rudder kicks, aileron pulses, and pitch pulses are used to check the damping. The Dutch roll, spiral mode, coordinated and uncoordinated banks, flat turns, and heading changes are also evaluated.

The preparation for approach involves the lowering of flaps and arming the spoilers. The ILS glideslope and localizer is intercepted at a 45° angle. The power is reduced to about 50% normal rated thrust, and the glideslope is followed until the 200-ft level is reached. At 200 ft, the video presentation appears with the runway randomly misaligned 200 ft either side of the localizer. This requires a rapid turn and bank maneuver for runway alignment. At 50-ft altitude, an instrument light reminds the pilot to reduce power, to idle and to initiate flare. When all the wheels are on the runway, the thrust is reversed and the nose gear is used to steer to runway centerline.

Cooper ratings were used to evaluate the pilot opinion of augmented and unaugmented aircraft. These numerical ratings were patterned after the ratings that were originated by George Cooper of NASA Ames. The Cooper ratings were imposed in lieu of adequate handling qualities criteria. A Cooper rating of 2.5 or better was required for the augmentation system. This numerical rating is described as somewhere between "satisfactory" and "pleasant to fly."

The analysis team used an offset maneuver to evaluate the coordination during the landing approach condition. In the offset maneuver, the aircraft breaks out of the overcast at 200-ft altitude and is displaced laterally a distance of 200 ft from the runway centerline. The pilot is required to bank and turn the aircraft sharply and return to wings level prior to touchdown. Any pilot or aircraft augmentation at this stage is sure to be appreciated. Without proper coordination, the yaw alignment with the runway is not precise and some sideslip may be present at touchdown. At low speeds it often is difficult for the pilot to sense sideslip angles since the present cockpit instruments are of little help.

The analog computers were used to determine control concepts prior to the simulator studies. These studies showed that the coordination at approach speeds and the pitch response needed the most attention. The coordination system must provide adequate yaw damping to gust disturbances, improve the Dutch-roll damping and keep the spiral divergence within limits. Dutch roll is so named because the roll and yaw oscillation resembles a Dutch ice skater. The system must also allow the pilot to command intentional sideslip to correct for crosswinds on the landing phase. The coordination is most needed for the offset maneuver where the flight must be precise rather than for conventional landings where the commanded bank angles are small.

The pitch response is important in following a glide path beam and in the final flare. The pilot must be able to make rapid changes with very little overshoot and a quick return to the trimmed condition. On takeoff, the pitch augmentation should provide adequate damping on the rotation and again provide a quick return to the trimmed climb angle. Since the pitch responses are normally well damped for the basic aircraft, it is very easy to provide an excess of damping and a slow return to trimmed flight. Since the phugoid motion frequency is close to the short-period frequency, the selection of the proper feedbacks is important. Most of the proposed specifications and requirements show that a problem exists but are not specific in what is required. The damping ratio needs no improvement since the C-5 damping is around 0.7 at many slow speed conditions. The short-period pitch frequency is low and for some approach conditions is around 0.14 cps. When this is coupled with the phugoid motion, the problem is more complex, since the frequency of the pitch response must be changed without increasing the damping ratio.

There are several aerodynamic parameters that are useful in describing the dynamic pitch characteristics of the aircraft. The pitch or flight path response is best described by two terms, T_a and $n_{z\alpha}$. Bretoi in 1955 (published in Ref. 3) described the pitch equations of motion in simplified form. The airplane time constant T_a is an indication of the airplane flight path response to a pitch attitude input.

$$\dot{\gamma} = \dot{\theta}/1 + T_aS$$

where $\dot{\gamma}$ = flight path rate of change, $\dot{\theta}$ = pitch rate of aircraft, S = Laplace operator, and T_a = airplane time constant. This time constant can be calculated from the aerodynamic characteristics of the airplane by the following approximation:

$$1/T_a \approx -Z_w$$

where Z_w = vertical force due to a vertical velocity change and is a function of the lift curve slope and the drag coefficient. The other term is the $n_{z\alpha}$ or the normal acceleration per unit angle of attack change. It can be calculated by the following relationship:

$$n_{z\alpha} = (1/T_a)U_1/g$$

where U_1 = forward velocity, ft/sec, g = acceleration due to gravity, ft/sec^2, $n_{z\alpha}$ = g/rad, and T_a = airplane time constant. For the C-5, the airplane time constant T_a is around two seconds, which is good for an aircraft of this size. The $n_{z\alpha}$ on some of the low-speed conditions is around 0.045 g/deg, which is relatively low. This characteristic, plus the low short-period frequency, makes the C-5 pitch response sluggish.

The roll augmentation is used to damp the Dutch-roll motion and also to increase roll damping to a manual pilot roll command. Here again, the offset maneuver is probably the most critical since the bank angles approach 30° and the command must be precise. If the roll damping is too high it will tend to slow down the roll into the turn and the desired 8° in the first second is compromised. In addition, compensation is necessary to keep the spiral divergence mode within limits. This is not normally a problem in the offset maneuver since the bank angle is held for only a short time, but it can become a problem in a go round. Here the pilot may combine a climbout with a gradual bank, and it becomes annoying to have to readjust the bank angle continuously because of spiral divergence.

Simulator Analysis

Several lateral-directional augmentation configurations were evaluated by the pilots on the C-5 simulator. A basic system, called a sideslip rate ($\dot{\beta}$) damper used the sideslip rate equation of motion as a source for the feedback signal. The sideslip rate signal to the rudder servo is similar to the NASA approach described in Ref. 4. This sideslip rate system provided good yaw damping without too much opposition to pilot-initiated turns. It also reduced the sideslip to reasonable limits in the low-speed approach flight conditions.

The NASA Ames study of Ref. 1 and 4 used a Lockheed NC-130B and was primarily interested in the stability and control characteristics of Short Takeoff or Landing (STOL) aircraft. In their studies they compared the conventional yaw rate damper system with a sideslip rate to rudder system. The sideslip rate system reduced the peak sideslip developed in a turn in comparison to the conventional yaw rate system. It also reduced the comparative steady-state sideslip and the steady-state oscillations. The yaw rate system was better for intentional sideslip maneuvers such as those required for landing in crosswinds.

The sideslip rate system was flight tested in the NC-130B to evaluate the β/ϕ (sideslip to roll) for the basic aircraft and the augmented system. At bank angles of 15° or greater the sideslip exceeded 5° where the desired ratio should not exceed 0.3. These tests also showed that the use of sideslip vanes or differential pressure required the sideslip signal to be heavily filtered in gusty air. The addition of the filter caused lag effects that would make the signal unsuitable.

However, a basic system similar to the NASA approach was used on the C-5 simulator. This system resembles the sideslip rate damper but uses conventional signals such as yaw rate, roll attitude and roll rate to implement the sideslip rate equation. It should be noted that previous attempts at obtaining a sideslip rate signal from a sideslip vane were not successful. NASA experience with the NC-130B indicated that the signal had to be heavily filtered to be useful. This system doesn't follow the sideslip rate equation exactly since the sideslip rate equation usually contains a roll attitude gravity term, yaw rate and lateral force terms. It seems logical to replace the lateral force terms with a lateral acceleration signal in order to complete the equation. The use of a lateral accelerometer has several serious drawbacks since the lateral acceleration is small for miscoordinated turns at low-speed approach conditions. If it is to be used, the gain of the signal to the rudder servo must be very high. This signal is also detrimental at higher speeds since it reduces the yaw damping by effectively changing the yaw controlled frequency. If the signal is lagged with a time constant of 5 sec or more, the yaw damping will improve but the coordination will still be marginal.

The system that gained the best pilot's ratings used yaw rate, roll rate, and roll attitude to the rudder servo for excellent turn coordination (see Fig. 1). The sideslip was less than 1° for a 30° bank in the approach condition and provided good Dutch-roll damping, although the control of the spiral mode became more difficult. Pilots were able to miscoordinate the aircraft deliberately, and upon rudder release the aircraft would smoothly return to center. The C-5, within the rudder authority limits, becomes a two-control aircraft. The design aim in the roll axis was to obtain 8° of roll in the first second on the approach conditions. Most transports, including the C-5, do not have excess rolling capabilities at low speeds and roll augmentation tends to decrease the roll rate capability at a time when it is most needed. As mentioned before, in addition to the yaw damper the roll augmentation is needed to damp out the Dutch roll oscillation. It also affects the spiral mode through the roll attitude feedback. The final selection of the roll rate feedback gain is somewhere between that required for good Dutch roll damping and adequate roll rate capabilities. In addition, roll stiffness in the form of a roll attitude signal was used to make the spiral mode neutrally stable. This provided just enough control so that the pilot need not devote too much attention to this mode. If the spiral mode is divergent, the pilot has to make constant corrections to the roll axis at the low speeds. With the yaw and roll augmentation system engaged, the pilot can make a reasonably precise roll without attention to the rudder axis and without undue roll corrections.

The requirements for the pitch augmentation of the C-5 are different from those of a typical transport. It may be recalled that the C-5 has a sluggish pitch response at the very low speeds since the phugoid or long-term motion is very close to the short-period frequency. The short-period damping is adequate with the damping ratios of around 0.7 but the problem occurs with the additional pitch augmentation. It is desirable to shorten the short-period response time without affecting the damping ratio.

The studies on the simulator with the augmentation system showed that the pilot did not want an increase in damping over the basic "free" aircraft. This is understandable when the "free" aircraft has a short-period damping of 0.7 (very little overshoot). However, the pilots did not like the interaction of the low frequency associated with the slow response and the phugoid or long-term frequency. After a pilot command of pitch attitude the free aircraft was slow to settle out on the new trim attitude. At cruise flight conditions and even intermediate speeds, this problem no longer exists and the aircraft has good handling characteristics.

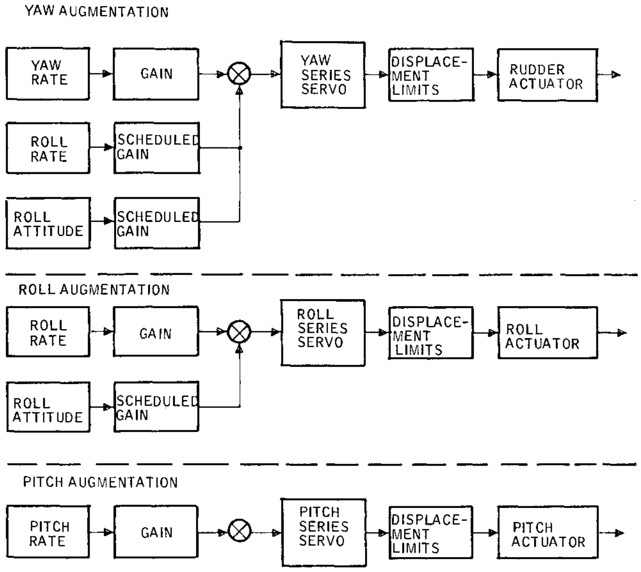

Fig. 1 Stability augmentation systems.

Pitch augmentation effects were analyzed primarily on the glide path and climb-out phase. In the climb-out the augmentation must provide proper damping on the rotation and capture of the climb path angle. After climb-out and push-over to level flight it should not restrict the trim to level flight. On the glide path, in preparation for landing, the augmentation must allow small corrections with adequate damping and precise tracking. The effects of pitch augmentation are most noticeable during the steep-angle approach as the pilot tries to maintain a constant descent angle. A maneuver of this type requires a good pitch response with adequate aircraft flare capabilities.

The final augmentation system used pitch rate for the long-term damping with a slight increase in short-term damping. The amount of overshoot is no problem since the damping ratio is high but the slow return to center can be a problem. This slow return is also objectionable during the glide path tracking phase where the pilot wants to get the aircraft back on the beam without a long solution time.

The final system corrected these problems to the point where the proper pilot augmentation was available for gust disturbances without giving too much pilot opposition for manual commands. This is provided up to the present series servo travel limits, which are adequate for normal maneuvering.

Conclusions

The augmentation systems were used on the first flight of the C-5 and subsequent flights with a performance comparable to that on the simulator. Judging from pilots comments, the simulator was a valuable tool in gaining preflight experience on the C-5. The landing and takeoff are generally problem areas in any aircraft and it was in these areas that the study effort was concentrated. The C-5 should provide an excellent vehicle for further handling quality research on large transports, since the pilot comments indicate that the handling qualities can now be specified in greater detail. A simulator could be used for these studies although the pilots said the aircraft had better damping than the simulator. With regard to sideslip requirements, it may be more useful to specify a maximum sideslip for any bank angle up to 45° instead of a sideslip to bank ratio. The analysis used a maximum allowable sideslip angle of 1° or less for the critical offset maneuver. With the lateral-directional augmentation during the low-speed approaches, the pilot can concentrate on the roll angle during turn maneuvers. His location with respect to the center of gravity and the high angles of attack detract from his ability to correctly sense sideslip. With the assistance of the augmentation system, he can develop the high roll rate and roll attitude necessary for final alignment with the runway. The augmentation system also provided near neutral spiral stability so that the roll attitudes were precise without any tendency to drift.

In the pitch axis the C-5 did exhibit the characteristics described in Ref. 2. The short-period frequency does interact with the phugoid so that what starts out as a short-period response has the long period superimposed. The conventional short-period handling qualities criteria and the frequency-damping criteria do not apply to the C-5. Actually the frequency seems to be more important to the pilot than the damping ratio. In general, the pitch augmentation is not as useful as the yaw augmentation system according to flight test reports.

The $n_{z\alpha}$ (normal acceleration per unit angle of attack) is important during the steep angle approach where the pilot must make the final flare. This term is important in describing the ability of the aircraft to arrest a high rate of descent during the flare or to establish a safe climb-out after decision to go-around. This term can be augmented by the use of direct lift devices such as drooped ailerons or landing flaps. This opens another possibility for the improvement in touchdown accuracy with direct lift devices.

In conclusion, the use of the simulator was very beneficial in predicting problems and verifying the solutions. The results have been most satisfying judging from pilots' comments during the early flight test phase.

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