FLIGHT TEST EVALUATION OF A SEPARATE SURFACE ATTITUDE COMMAND CONTROL SYSTEM ON A BEECH 99 AIRPLANE

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Abstract

A joint NASA/university/industry program was conducted to flight evaluate a potentially low cost separate surface implementation of attitude command in a Beech 99 airplane. Saturation of the separate surfaces was the primary cause of many problems during development. Six experienced professional pilots made simulated instrument flight evaluations in light-to-moderate turbulence. They were favorably impressed with the system, particularly with the elimination of control force transients that accompanied configuration changes. For ride quality, quantitative data showed that the attitude command control system resulted in all cases of airplane motion being removed from the uncomfortable ride region.

Introduction

An attitude command control system for general aviation was flight tested at the NASA Dryden Flight Research Center. (1 to 3) In attitude command control systems, the pitch and roll attitudes of the aircraft, through the use of feedback controls, follow the positioning of the pilot's control wheel. The pilot is part of the closed loop system and maneuvers the aircraft with the system. A fly-by-wire mechanization of this concept greatly improves airplane handling and riding qualities; however, the high cost of installation makes this type of mechanization impractical for general aviation applications.

The University of Kansas has been studying the application of separate surfaces for general aviation. (4 to 6) The use of separate surfaces for attitude command appears to be logical in that its cost is low, it meets flight safety requirements, and it is easy to install in existing airplanes. Consequently, a grant was awarded to the University of Kansas to study the feasibility of and designs for attitude command using separate surfaces. (7) Improvements in handling and ride qualities in commuter airline operations would provide an economic advantage, and a Beechcraft Model 99 airplane was chosen because it was representative of commuter airline transports. The University was eventually awarded a contract to design, fabricate, install, and flight test a separate surface system on this airplane. Much of this work is reported in References 8 to 11. The Beech Aircraft Corporation and The Boeing Company, Wichita Division, also participated in the program.

*Member, AIAA.

Symbols and Abbreviations

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$F_w$</td>
<td>pilot-applied control wheel force, pounds</td>
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<td>IFR</td>
<td>instrument flight rules</td>
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<td>ILS</td>
<td>instrument landing system</td>
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<tr>
<td>$K$</td>
<td>gain constant</td>
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<tr>
<td>KIAS</td>
<td>knots indicated airspeed</td>
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<tr>
<td>$p$</td>
<td>roll rate, degrees per second</td>
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<tr>
<td>$q$</td>
<td>pitch rate, degrees per second</td>
</tr>
<tr>
<td>$r$</td>
<td>yaw rate, degrees per second</td>
</tr>
<tr>
<td>$\text{rms}$</td>
<td>root mean square</td>
</tr>
<tr>
<td>$s$</td>
<td>Laplace operator function</td>
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<tr>
<td>TIMS</td>
<td>turbulence intensity measurement system</td>
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<tr>
<td>$t$</td>
<td>time, seconds</td>
</tr>
<tr>
<td>$\beta$</td>
<td>sideslip, degrees</td>
</tr>
<tr>
<td>$\delta$</td>
<td>control surface deflection, degrees</td>
</tr>
<tr>
<td>$\theta$</td>
<td>pitch attitude, degrees</td>
</tr>
<tr>
<td>$\dot{\theta}$</td>
<td>pitch rate, degrees per second</td>
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<tr>
<td>$\tau$</td>
<td>time constant, seconds</td>
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<tr>
<td>$\varphi$</td>
<td>roll attitude, degrees</td>
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<tr>
<td>$\phi$</td>
<td>roll rate, degrees per second</td>
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<tr>
<td>$\psi$</td>
<td>heading attitude, degrees</td>
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<tr>
<td>$\Delta\psi$</td>
<td>increment of heading change, degrees</td>
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Subscripts:

<table>
<thead>
<tr>
<th>Subscript</th>
<th>Description</th>
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<tbody>
<tr>
<td>$ap$</td>
<td>primary aileron (right)</td>
</tr>
<tr>
<td>$as$</td>
<td>separate surface aileron (right)</td>
</tr>
<tr>
<td>$ep$</td>
<td>primary elevator</td>
</tr>
<tr>
<td>$es$</td>
<td>separate surface elevator</td>
</tr>
<tr>
<td>$f$</td>
<td>wing flap</td>
</tr>
<tr>
<td>$H$</td>
<td>horizontal stabilizer</td>
</tr>
<tr>
<td>$rp$</td>
<td>primary rudder</td>
</tr>
<tr>
<td>$rs$</td>
<td>separate surface rudder</td>
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Program Objectives

The program objectives were to perform a flight evaluation of the operational characteristics and performance of a potentially low cost separate surface implementation of attitude command on a Beech 99 airplane and to provide the general aviation industry with a first hand evaluation of the control concept by allowing their participation.
**System Description**

**Aircraft**

Figure 1 is a three-view drawing of the Beech 99 aircraft with separate control surfaces. The aircraft is a twin-engine, turboprop, 17-place commuter airliner. It has a wingspan of 46 feet, a length of 45 feet, and a maximum gross weight of 10,400 pounds. It has a maximum cruise of 244 knots at 16,000 feet and a service ceiling of approximately 28,000 feet. Its approach speed is 96 knots, and it is capable of operating off a 3000-foot runway.

**Hardware Implementation**

The flight control system modifications consist of electrically interconnected components and include a gyro package, a management and control panel, an operator's console, and electromechanical actuators, which drive small separate control surfaces.

The gyro package consists of a vertical gyro, directional gyro, and three rate gyroes; and it is mounted in the proximity of the center of gravity of the airplane.

The management and control panel (Fig. 2) contains switches, lights, surface position indicators, and potentiometers; and it is installed in the copilot's instrument panel.

The operator's console contains all the electronics for control law computations, gain adjustment, servo amplifiers, ground tests, and power supplies. The unit is installed in the main cabin.

The control actuators are of the electromechanical screw jack type. They require 28 volts dc and produce approximately 400 pounds of linear force at a maximum current of approximately 10 amperes. The frequency response of the actuators is approximately 1.5 hertz. They are located in the wings and tail with the separate control surfaces.

**Separate Control Surfaces**

The separate control surfaces for attitude command are obtained by the dichotomy of the primary control surfaces. In sizing the separate surfaces, consideration was given to static control and the avoidance of saturation. The sizes calculated met the military and civil aircraft performance standards (MIL-F-8785C and FAR Part 23, respectively) for failed hardover conditions. In the roll axis, 39 percent of the total roll control power is provided by the separate surface ailerons; in the pitch axis, 25 percent of the total pitch control power is provided by the separate surface elevators; and in the yaw axis, 27 percent of the total yaw control power is provided by the separate surface rudder.

**System Operational Modes**

Three modes of system operation are provided: off, slave, and command. A control panel in the copilot's instrument panel allows the pilot to select one of these control modes and the control loops in the command mode.

In the off mode, the separate surfaces are deenergized, and the aircraft flies with approximately two-thirds of its original control power.

In the slave mode, the separate surfaces are electronically slaved to and operate in unison with the primary control surfaces; thus, the basic Beech 99 configuration is restored.

In the command mode, all three axes can be operated individually or in combination; however, all tests were combined-axis tests. The separate surfaces hold the aircraft in the attitude commanded by the position of the pilot's control wheel in the pitch, roll, and yaw axes. Heading is maintained by a combination of roll and yaw heading hold control loops. Yaw-damper-only operation is available in the yaw axis.

The system is designed to operate at the approach and cruise flight conditions.

**Pitch axis**. A block diagram of the pitch axis is shown in Figure 3(a). The pilot controls the primary surface through the mechanical control system and has an electric trim system to position the horizontal stabilizer.

In the slave mode, the primary surface position, through the appropriate slave gain, is used to position the separate surface; thus, the separate surface operates in unison with the primary surface.

In the command mode, when the pilot commands a pitch attitude through the control column, the primary surface position is fed back through the appropriate gain and compared with the actual pitch attitude. The difference between commanded and actual attitudes is filtered and drives the separate surface to reduce the difference to zero by changing the actual attitude of the aircraft. Thus, the attitude of the aircraft becomes proportional to control column displacement.

The separate surface has a streamline position detector which moves the horizontal stabilizer through the autotrim system to keep the separate surface at a near zero position.

**Roll axis**. A block diagram of the roll axis is shown in Figure 3(b). It functions like the pitch axis except that it is coupled with the yaw axis. In the command and heading hold modes, and when zero bank is commanded, the yaw axis heading is locked. When the pilot applies an aileron wheel force to roll, the yaw axis unlocks to permit aircraft maneuvering.

**Yaw axis**. A block diagram of the yaw axis is shown in Figure 3(c). In the command, yaw damper, and heading hold modes, heading and heading rate are fed back to the separate surface to keep the aircraft on the heading sensed by the directional gyro. As explained above, the yaw axis automatically unlocks when the pilot maneuvers the aircraft for heading changes and locks when a new heading is established. The pilot can select yaw-damper-only operation, which manually unlocks the yaw axis by opening the heading feedback loop.

**Instrumentation**

A pulse code modulation digital data tape instrumentation system was installed in the aircraft to allow the debugging of the system, optimization of system performance, and acquisition of quantitative data from the flight test program. Seventy-seven channels at 200 samples per second are available for recording aircraft and system parameters.
A turbulence intensity measuring system (TIMS) \(^{(12)}\) was installed in the airplane to record the atmospheric gust velocity encountered during flight.

Figure 4 shows the mechanization of the turbulence-intensity measurement system. A pitot-static probe and a differential pressure transducer measure the longitudinal pressure fluctuations in front of the airplane. A bandpass filter attenuates deviations above 20 hertz and below 6 hertz to exclude unwanted high-frequency noise and low-frequency airplane response to turbulence and control inputs. The signal is then integrated in the computer and recorded in the data system. The computer also compensates for variations in the signal due to airplane velocity.

The recorded signal is directly proportional to the shaded area in the turbulence power spectrum in Figure 4. The power spectrum shown represents the standard format for quantitative turbulence measurements. This format is the result of extensive turbulence research which showed empirically that the log-log plot of the gust-velocity power spectrum is linear and has a constant and repeatable slope throughout the wavelength range from 10 feet to 10,000 feet. Therefore, changes in turbulence intensity change the magnitude of the spectrum but not its slope. The invariance of the slope is illustrated in the figure by the levels of light-to-moderate and moderate-plus turbulence spectra. Therefore, the shaded area varies directly with the level of turbulence intensity. This area is also directly proportional to the root-mean-squared value of the gust velocity, which is equal to the magnitude of the area under the entire power spectral curve.

**Developmental Problems**

As with most flight programs, problems were encountered with the system during the initial phases of flight. Some of these developmental problems, which may be unique to this system, are discussed below.

**Pitch Trim Overshoot**

When the pilot commanded a new pitch attitude with a trim input, the aircraft overshot the commanded attitude and then gradually returned to it. The problem was duplicated on the University of Kansas simulator, and, as shown in Figure 5, the separate surface is saturated, allowing the pitch attitude to overshoot. The problem is the result of differences in aircraft responses from separate surface inputs and trim inputs. The pitch trim overshoot was eliminated by adjusting the command gain to the separate control surfaces, as shown in Figure 6.

**Bank Angle Overshoot**

Figure 7 is a time history showing a step input of 5.6° primary aileron for a 12° bank angle, and a resulting 5° bank angle overshoot. Immediately before the bank angle overshoot, the separate surface aileron saturates (it has a 14° limit), and an overshoot ratio of 42 percent results. The forward loop gain is 15.

The overshoot ratio is a function of forward loop gain (Fig. 8). Increasing the gain to 60 results in an acceptable overshoot. Increasing the gain requires less primary control surface deflection, and therefore less separate surface authority, for a commanded bank angle; however, the gain is limited by too abrupt control response and excessive control sensitivity.

**Heading Hold Operation**

The system was originally mechanized to unlock the heading loop when the pilot's control wheel deflected more than 30°. While this technique was satisfactory for a Piper airplane, \(^{(3)}\) it was unsatisfactory for the Beech 99 airplane because of high control system friction and forces. The problem was resolved by replacing the aileron position sensor with a torque-sensitive switch on the control wheel that was activated by a very small wheel force.

**Pitch Changes With Configuration Changes**

One benefit of the attitude command system is the elimination of pitch changes during aircraft configuration changes. However, the elevator's separate control surfaces saturated during a go-around maneuver, which resulted in the airplane's pitching down. Analysis of the problem indicated that the nose-down pitching moment was generated by flap retraction and that the autotrim rate could not keep up with the changes. It seemed logical to limit the rate of configuration changes to avoid saturation. It was not practical to reduce the flap retraction rate; however, a successful fix resulted from interrupting the flap retraction whenever the autotrim system was operating.

**Test Plan and Procedures**

Six pilots participated in the qualitative flight evaluation. All were experienced professional pilots. Three were general aviation pilots who were twin-engine, instrument rated, but had no experience in the Beech 99 airplane. The other three were NASA research pilots. All pilots were given a 1-hour familiarization flight in the basic Beech 99 airplane.

The flight test pattern for the qualitative pilot evaluation is shown in Figure 9. The vertical-8 maneuver is a series of climbing and descending turns. The 90° localizer interception was initiated from the cruise configuration to increase the difficulty of the piloting task. The flights were conducted under simulated instrument flight conditions. Each pilot flew the entire pattern in the slave mode and then immediately repeated the pattern in the command mode. Only two pilots repeated the flights.

The piloting task was evaluated with the Cooper-Harper rating scale. \(^{(13)}\) The ratings range from 1 to 10, where 1 indicates excellent controllability and 10 indicates that control will be lost during some portion of required operation.

**Flight Test Results**

**Aircraft Response Characteristics**

**Roll axis.** The response to an aileron step input in the command mode is shown in Figure 10. The separate surface aileron starts in the direction of the primary aileron and opposes it when the desired bank is reached; thus, the bank angle becomes proportional to the pilot's control deflection.
Pitch axis. The response to an elevator step input in the command mode is shown in Figure 11. Again, the separate surface elevator produces a change in attitude proportional to the pilot's control deflection.

The control force transients in the slave mode during configuration changes are shown in Table 1. The elevator wheel forces required to trim are high, and can rise as high as 70 pounds during a go-around maneuver. Depending on the duration of the transient forces, pilots generally oppose the forces rather than trim. These transient forces, and the accompanying pitch changes, are eliminated in the command mode. The flap interrupt modification about doubles the normal flap retraction time, and Figure 12 shows a hands-off vehicle response during a configuration change.

Yaw axis. The most significant change that occurred in the yaw axis with the command mode is the yaw damping effect. Figure 13 shows the response of the aircraft to a rudder doublet in the slave mode. Dutch roll damping is low. Figure 14 is the aircraft response in command mode to a rudder doublet. Dutch roll damping is improved.

Pilot Evaluations

This flight test program is oriented towards the generation of pilot opinions concerning the handling and ride qualities of the modified Beech 99 airplane. The flight profile reflects this philosophy. The maneuvers are designed to task the pilot to enable him to evaluate the changes in aircraft dynamics, although the profile does not depart from being a realistic IFR mission. Therefore, the pilots' comments and the Cooper-Harper pilot ratings constitute the most important results of the flight tests.

After the pilots performed the mission in the slave and command modes, they were debriefed. The following discussion gives the pilots' consensus of opinion concerning the handling qualities of the test airplane.

The pilots were favorably impressed with the elimination of the control force transients that accompanied configuration changes. They seemed to like the pitch stabilization provided by the attitude command system; however, some pilots tended to resist adapting to the system. Comments characterizing this discussion are presented in Table 2.

Holding aileron force during turns was annoying. Most pilots stated that they did not like using the aircraft's manual trim. Some pilots thought that a wheel-mounted electric trim might be acceptable. One pilot said he felt that it was unsafe to trim to some bank angles.

The workload was greatly reduced by the command mode, especially for precision maneuvers like localizer and glidepath tracking. The improvement was even more pronounced in turbulence.

Most pilots agreed that with the attitude command system on, the ride qualities and turbulence response of the aircraft were substantially improved. Comments regarding ride qualities are presented in Table 3.

Pilot Ratings

The nonresearch pilots had not used the Cooper-Harper rating scale before. Perhaps as a consequence of this, their ratings did not indicate much improvement when the attitude command system was on; however, their unrecorded comments and enthusiasm after flying with the system indicated that the airplane flew better than they had expected, and that they were pleased with the operation of the system.

The pilot ratings generated from the flight profile as a function of turbulence are presented in Figure 15. The TMS output in rms volts is correlated with the pilot assessment of the turbulence level in the slave mode. In the command mode, the pilot rating shows an improvement of at least 0.5 over the airplane in the slave mode. The mean improvement in pilot rating is between 1.25 and 1.50.

The instrument approach is the most demanding of all the piloting tasks. A measure of pilot workload for this task is shown in terms of aileron activity in Figure 16. There is substantially less aileron activity in the command mode. Figure 17 shows the standard deviation in heading versus turbulence. Although the figure shows no significant improvement in performance, the pilots felt that their performance was improved.

Ride Qualities

The precision heading task is typical of enroute flight of commuter airliners. Atmospheric turbulence during these evaluations was light to moderate. The vertical and transverse accelerations of the aircraft are shown in Figure 18. The solid symbols represent the averages of six flights. In terms of percentages, the data show an 18.5-percent reduction in vertical acceleration and a 32.2-percent reduction in transverse acceleration when the system is in the command mode.

The effects of attitude command on passenger comfort are also apparent in Figure 18. Boundaries of passenger comfort were extracted from studies of passenger ride quality determined from commercial airline flights in which a Beech 99 airplane was one of several aircraft used. (14) Passenger comfort responses in light-to-moderate turbulence are generally borderline to uncomfortable when the airplane is in the slave mode. In all cases, putting the airplane in the command mode removes it from the uncomfortable region.

Concluding Remarks

Flight testing the Beech 99 airplane demonstrated separate surface controls to be a viable approach to improving both the handling and ride qualities of current general aviation aircraft. Separate surface saturation was the primary cause of the problems encountered during the development of the system. The pilots were favorably impressed with the system, particularly with the elimination of control force transients that accompanied configuration changes. For ride quality, quantitative data showed that the attitude command control system resulted in all cases of airplane motion being removed from the uncomfortable ride region.
While there are many good features about attitude command control, there are some disadvantages of using separate surfaces for this application. The pilots tend to resist adapting to the control system, and they don't like holding aileron force during turns.

References


Table 1. Control Force Transients

<table>
<thead>
<tr>
<th>Configuration change</th>
<th>Elevator wheel force required to maintain attitude, in (pounds)</th>
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<tr>
<td>Gear down</td>
<td>7.5</td>
</tr>
<tr>
<td>Flaps down</td>
<td>50.0</td>
</tr>
<tr>
<td>Half to full power</td>
<td>18.0</td>
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Table 2. Handling Qualities Comments

Pitch attitude command:

I liked the decoupling effect of being able to control the glide slope and the rate of descent with the pilot trim and the speed with power.

Glide slope was more positive with the system on.

Pitch attitude command is probably the biggest improvement that I see in that the attitude tends to be locked in.

Not much change in the pitch axis except for the gear and flap transients.

Missed approach much easier, aircraft well controlled.

When the go-around was executed, I was forced to establish a climb attitude. The basic aircraft would naturally pitch up with acceleration.

Roll attitude command:

The workload is much lower, especially in the roll axis; I felt much more confident of my ability to perform the mission.

The localizer was easier to maintain.

Heading hold:

The basic aircraft wallows around. It is difficult to hold heading. The aileron forces are high. When you turn your system on, it relieves the pilot workload, particularly when maintaining heading in turbulence. If turbulence knocks you off the heading, the system brings you back to it.

Initially I was fighting the heading hold system; I wasn’t turning loose and letting it settle down. I found out later if I flew almost hands off, heading hold was pretty good.
In all the axes, as soon as you turn the attitude command on it seems as if the turbulence decreases by half. The ride is much smoother. The airplane seems as if it is on a rail or track.

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**Table 3. Ride Quality Comments With Attitude Command System On**

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<tr>
<th>Attitude Command System On</th>
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<td>In all the axes, as soon as you turn the attitude command on it seems as if the turbulence decreases by half.</td>
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<tr>
<td>The ride is much smoother.</td>
</tr>
<tr>
<td>The airplane seems as if it is on a rail or track.</td>
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Fig. 3 Mechanization of attitude command control system.
Electrical — Aerodynamic — Mechanical

Yaw damper only

L

Yaw damper
and
heading hold

Position potentiometer

Separate surface

Position potentiometer

Power amplifier

Actuator

Primary surface

Aircraft

Command

Off

Slave

Fig. 3 Concluded.

Fig. 4 Turbulence-intensity measurement system.
Fig. 5 Simulator pitch axis response due to pilot trim input with $K_{ep}^p = 10$. (Pitch angle overshoot induced by $\delta_{es}$ saturation.)

Fig. 6 Simulator pitch axis response due to pilot trim input with $K_{ep}^p = 20$.

Fig. 7 Time history of bank angle overshoot. Gear and flaps down; airspeed = 110 knots; $K_{ap}^p = 15$.

Fig. 8 Effect of $K_{ap}^p$ on overshoot ratio. Flight data.
Fig. 9 Qualitative flight profile.

Fig. 10 Aileron step response. Command mode.

Fig. 11 Elevator step response. Command mode.

Fig. 12 Aircraft response to configuration changes. Hands off, $K_0 = 20$, $K'_0 = 4$, $K_{\delta_{ep}} = 24$. 

1. Vertical-S maneuver (7 min)
2. Precision heading maneuver (10 min)
3. 90° localizer interception (3 min)
4. ILS approach (7 min)
5. Go-around (5 min)
Fig. 13 Aircraft response to rudder doublet in slave mode.

Fig. 14 Aircraft response to rudder doublet in command mode.

Fig. 15 Pilot ratings versus turbulence for tasks 3, 4, 5.

Fig. 16 Standard deviation of primary aileron versus turbulence. Task 4.
Standard deviation of heading, \( \sigma = 2 \) deg

Fig. 17 Standard deviation of heading versus turbulence. Task 2.

Passenger comfort response contours.

Fig. 18 Passenger comfort response contours.