General Aviation Application of Separate Surface Stability Augmentation

W. R. Bolton*
Sandia Laboratories, Livermore, Calif.
and
D. J. Collins†
Gates Learjet, Wichita, Kan.

A design and development project undertaken to provide the benefits of full-time stability augmentation at a cost low enough to encourage application in general aviation aircraft is described. The stability augmentation investigated was attitude command mechanized through separate control surfaces. With attitude command, the automatic control system maintains aircraft attitude proportional to pilot control deflection, despite disturbances such as atmospheric turbulence. Piloted flight simulation indicates that significant improvements in aircraft flying qualities may be provided by attitude command. The separate surface attitude command concept will be investigated and demonstrated in a flight test program on a Beech Model 99 modified for this purpose.

Introduction

PREVIOUS studies have investigated the handling and rise qualities benefits for general aviation aircraft that can result from the use of active stability augmentation control systems.[1] To find general application, such a system must be relatively inexpensive, simple, safe, and compatible with existing general aviation design practice. One approach to satisfying these objectives is through separate surface stability augmentation. The term "separate surface" refers to control surfaces, dedicated exclusively to a stability augmentation system, that are separate from and independent of the primary or pilot controlled control surfaces. Figure 1 illustrates a typical separate surface installation.

When used as the mechanization for stability augmentation, separate surfaces offer these advantages: 1) They eliminate force feedback through pilot controls typical of general aviation autopilots. The absence of these disturbing forces encourages the full-time use of stability augmentation. 2) If properly sized, even "worst-case" separate surface failures are easily controlled by the pilot. 3) The absence of hazardous failures makes it possible to eliminate system redundancy, with a resulting reduction in system complexity and expense. 4) Electric surface actuation eliminates the need for a hydraulic system (not available on most general aviation aircraft). 5) By subdividing the existing control surfaces, separate surfaces are simple to retrofit to current aircraft. 6) Once installed, separate surfaces are easily adapted to a variety of uses (stability augmentation, autopilot functions, active ride control, etc.).

The characteristics of separate surfaces are being investigated and demonstrated in a design and development program conducted at the University of Kansas (K.U.). Documentation of this program through April 1974 may be found in Ref. 2. Under sponsorship of the Flight Research Center of the National Aeronautics and Space Administration, K.U. has designed a three-axis separate surface stability augmentation system that will be installed and flight tested on a Beech Model 99 "Airliner." The stability augmentation control law for this program was patterned after the NASA Attitude Command System described in Ref. 1. In attitude command, the control system maintains the aircraft attitude in a fixed proportion to the cockpit control deflection, despite external disturbances such as atmospheric turbulence. Figure 2 shows a comparison between the step response of an unmodified aircraft (rate command) and the same aircraft with attitude command functioning.

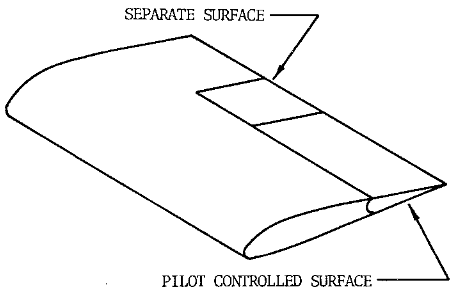

Fig. 1 Typical separate surface installation.

Attitude command offers the following desirable characteristics: 1) The control system maintains the aircraft in a level flight attitude without pilot attention. 2) Attitude upsets caused by atmospheric turbulence or other disturbances are eliminated. 3) Long time-constant aircraft motions, such as the spiral and phugoid, are eliminated. 4) Trim changes due to power setting or flap and landing gear position are eliminated. 5) Subjective evaluation of aircraft ride qualities is improved through a reduction of attitude excursions in turbulence and improved dutch roll damping.

Hardware Development

Characteristics of the separate control surfaces were predicted using the methods of Ref. 3. Early in the development program, windtunnel tests were conducted to verify these prediction methods and to investigate hinge moments induced on pilot controls by deflections of separate surfaces. As a result of these windtunnel tests it was concluded that 1) these prediction methods were adequate, 2) separate surfaces could be aerodynamically effectively located either inboard or outboard of the primary surface, and 3) induced hinge moments were negligible. The last conclusion tends to satisfy one of the basic objectives of the program, that is, separate surfaces can be effective without inducing undesirable force feedback through the pilot controls. This result has been further con-

Presented as Paper 74-860 at the AIAA Mechanics and Control of Flight Conference, Anahein, Calif., August 5-9, 1974; submitted October 1, 1974; revision received February 18, 1975.

Index categories: Aircraft Handling, Stability, and Control; General Aviation Systems.

*Member of Technical Staff, Systems Development Dept.

†Senior Engineer.

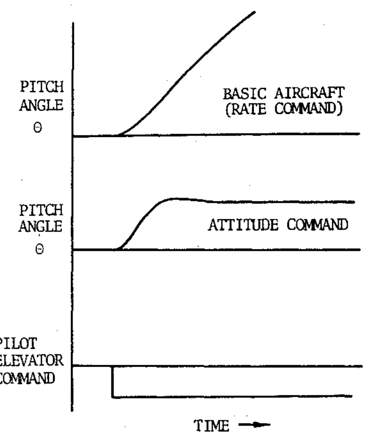

Fig. 2 Elevator step response comparison of unmodified and attitude command aircraft.

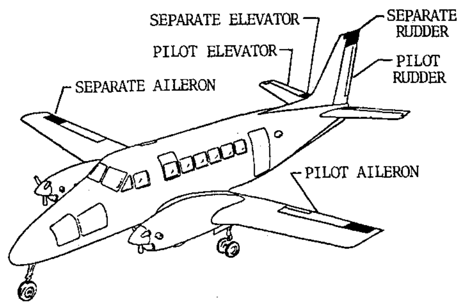

Fig. 3 Arrangement of Beech Model 99 separate and pilot-controlled surfaces.

firmed through the flight test of a separate surface equipped light aircraft.[4]

The modifications necessary to install a separate surface system include the separate surfaces, surface actuators, and drive and control electronics. K.U. has designed the installation for the Beech Model 99 testbed aircraft. The location of the separate surfaces, as shown in Fig. 3, was selected on the basis of manufacturing ease. These locations required the minimum modification to existing aircraft controls and structure. For example, the original trim tabs and cable actuation were retained on the pilot surfaces. The separate surfaces are installed essentially by cutting each existing surface into a primary and separate segment and adding required hinges and mounting hardware. This approach results in a low-cost separate surface installation.

Proper surface sizing is essential to a successful separate surface system. There are two primary considerations affecting separate surface sizing: static trim following a failure and surface saturation. Separate surface saturation refers to nonlinear behavior of the surface caused by a performance limit of the actuator (position, rate, force, etc.). Static trim considerations are most important to safety of flight, and will be discussed first.

The severity of a separate surface hardover failure‡ is directly related to the amount of control power available to the separate surface. Therefore, static trim sizing is concerned with balancing the separate surface control power and pilot surface control power to eliminate hazardous failures. This process will be illustrated with the example of sizing the Model 99 separate ailerons and rudder. In the lateral axis, it is assumed that some failure results in a hardover failure of both separate surface ailerons. To retain control of the aircraft, the pilot must have sufficient control power to trim rolling moment caused by the failure. To consider this a nonhazardous failure, the pilot must have enough additional control power to maneuver the aircraft for a successful landing. Unfortunately, the Federal Aviation Regulations offer no criteria

‡A hardover failure occurs when a separate surface drives to and remains at a surface deflection limit.

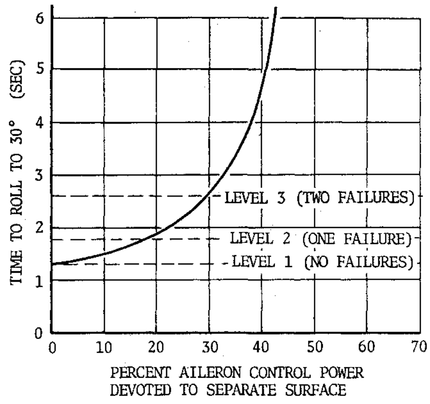

Fig. 4 Effect of separate surface size on lateral maneuvering following a hardover separate aileron failure.

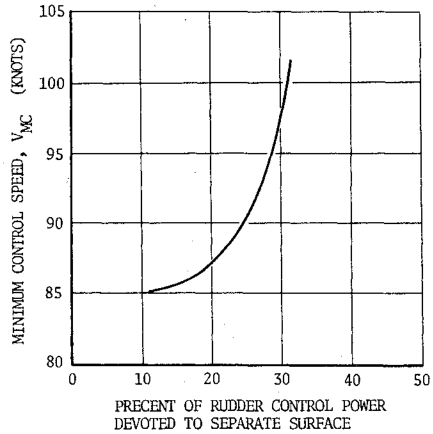

Fig. 5 Effect of separate rudder size on minimum control speed.

for evaluating the handling qualities of an aircraft following such a failure. Therefore, the criteria of the Military Flying Qualities Specifications (MIL F-8785B),[5] were adopted. Figure 4 illustrates the effect of separate surface size on maneuvering an aircraft following a hardover separate surface aileron failure. Notice that if no control power is devoted to the separate ailerons, a hardover failure has no effect. If half the available control power is devoted to the separate aileron, the pilot is just able to trim the moment and has no control power remaining to maneuver the aircraft. Level 3 controllability, which corresponds to the desired level of maneuverability following the aileron failures, is satisfied with 30% of the lateral control power devoted to the separate aileron. This is the separate aileron size selected for the Model 99.

In the directional axis, there is no requirement for maneuvering following a hardover failure. However, the rudder must be sized with consideration for the possibility of an engine failure in addition to a separate rudder hardover. The pilot must have sufficient control power to balance an engine failure and a separate rudder hardover into the dead engine at an acceptable minimum control speed. Figure 5 shows the effect of separate rudder size on minimum control speed on the Model 99. The maximum allowable minimum control speed was selected to be 88 knots. This specified the maximum separate rudder size at 24% of available directional control power.

Three types of saturation occur in a separate surface control system: 1) rate saturation, 2) hinge moment saturation, and 3) deflection saturation. Actuators typically have maximum force and velocity limitations. The actuator force limit produces the surface hinge moment saturation threshold and the actuator velocity limit produces the surface rate saturation threshold. These thresholds tend to be inversely related and are primarily affected by the actuator-to-surface linkage design. That is, increasing the actuator mechanical advantage will increase the hinge moment and decrease the rate threshold, and decreasing the actuator mechanical advantage will decrease the hinge moment and increase the rate threshold. The optimum actuator linkage is usually selected to provide the maximum rate saturation threshold without hinge moment saturation in the desired operating envelope of airspeed and altitude. Notice that hinge moment saturation can be used to limit the effect of hardover failures at high dynamic pressure flight conditions.

Deflection saturation may result during flight through atmospheric turbulence. Methods have been developed at K.U. for predicting deflection saturation due to turbulence based on statistical methods.[6] Figure 6 shows the probability of deflection saturation as a function of separate surface size for the Model 99. Since the Model 99 uses a powerful horizontal stabilizer for longitudinal trim, any size separate surface elevator could be trimmed in a hardover failure. Therefore, static trim does not provide an elevator sizing criterion. In the absence of other criteria, deflection saturation in turbulence was used to size the separate elevator. The elevator size was selected to give the same probability of saturation as the separate aileron. As seen in Fig. 6, this resulted in 25% of the available elevator control power being devoted to the separate surface elevator.

Deflection saturation may also occur as a result of pilot inputs. This effect is very dependent upon configuration and the control law employed. Pilot induced deflection saturation is most likely to be encountered in the Model 99 roll axis. The control system achieves attitude command by balancing the rolling moment resulting from pilot aileron input with separate aileron deflection at the commanded bank angle. The attitude command authority limit is reached at that bank angle that requires full separate aileron deflection. Should the pilot command a bank angle in excess of the authority limit, the aircraft response transitions from attitude command to rate command. The pitch and roll authority limits for the Model 99 system are: pitch axis—$\theta = \pm 10°$; roll axis—$\phi = \pm 30°$. Flight simulation indicates that the rate command transition resulting from pilot induced deflection saturation is not objectionable for the Model 99 system. However, this effect should be evaluated for each system configuration.

As mentioned earlier, most general aviation aircraft are not equipped with hydraulic systems. Therefore, only electromechanical actuators provide adequate performance using existing aircraft systems. A piloted simulation was conducted at the K.U. fixed-base flight simulator to investigate the minimum required actuator performance. This simulation indicated that the pilot's opinion of attitude command was unaffected by actuator dynamics provided the corner or break frequency of the actuator was approximately 7 rad/sec or higher. An extensive hardware survey was undertaken to identify an actuator possessing the desired characteristics. The actuator selected was a d.c. electric recirculating ball screw type manufactured by McDonnell-Douglas Electronics. The drive and control components used in conjunction with these actuators are shown schematically in Fig. 7.

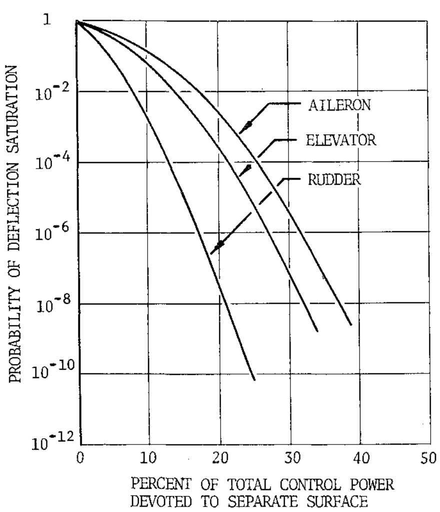

Fig. 6 Probability of deflection saturation at landing flight condition.

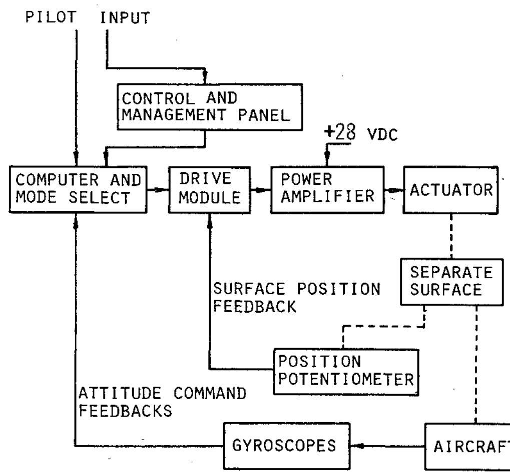

Fig. 7 Block diagram of typical separate surface actuator drive system.

Prototype components of the separate surface system were installed on a bench test fixture called the "Iron Bird." The Iron Bird was arranged to duplicate the actual aircraft installation, as much as was practical. The actuators were connected to simulated separate surfaces that matched the moment of inertia and aerodynamic hinge moments of the testbed aircraft. The Iron Bird, which proved to be very valuable during the system development, was used for these purposes: 1) to develop compatibility of all system components, 2) to demonstrate proper operation of the system, 3) to investigate the reliability of system components, 4) to assist with the system fault analysis, and 5) to provide separate surface deflections for the piloted flight simulation.

Attitude Command Development

Figure 8 is a block diagram of the Model 99 attitude command longitudinal axis. The longitudinal axis is typical of the attitude command concept, and will be used to illustrate its development. In attitude command, the aircraft attitude is forced to be directly proportional to the cockpit control displacement. Therefore, the pilot elevator deflection signal is effectively an attitude reference signal. The error between the attitude reference and the aircraft attitude is added to an angle rate feedback to form the command voltage to the separate elevator. With the fundamental control philosophy selected, the remainder of the design involves these steps: 1) Using root locus techniques select any required series compensation and define ranges of feedback gains that result in adequate damping of all modes, 2) Add any desired special functions, for example, attitude reference trim in the longitudinal axis. 3) Using piloted simulation, investigate pilot acceptance and adequacy of the design. 4) Redefine gains and compensation, as required, to obtain satisfactory system operation.

The longitudinal axis series compensator contained a pole at the origin of the s-plane. The effect of this pole is to prevent the system from accepting any deviation from the commanded pitch attitude. Therefore, the system will maintain the commanded attitude despite steady-state pitching moment changes caused by landing gear, flaps, power changes, etc.

Once the gains and compensation were selected to give the desired frequency domain characteristics, the longitudinal trim system was incorporated, as shown in Fig. 9. The trim system was designed to be compatible both with the existing

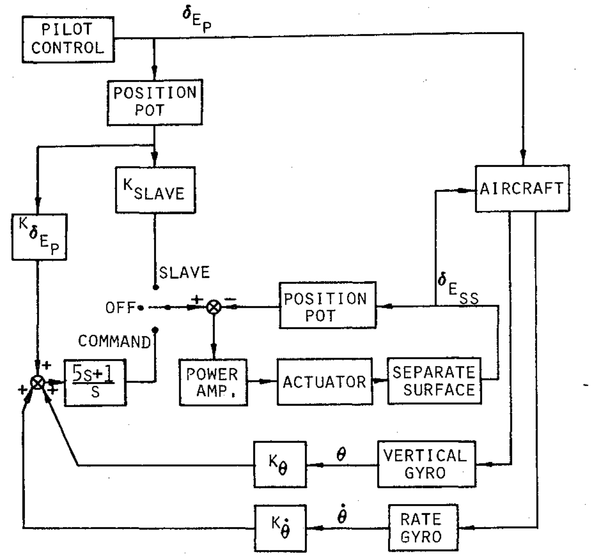

Fig. 8 **Block diagram of longitudinal attitude command system.**

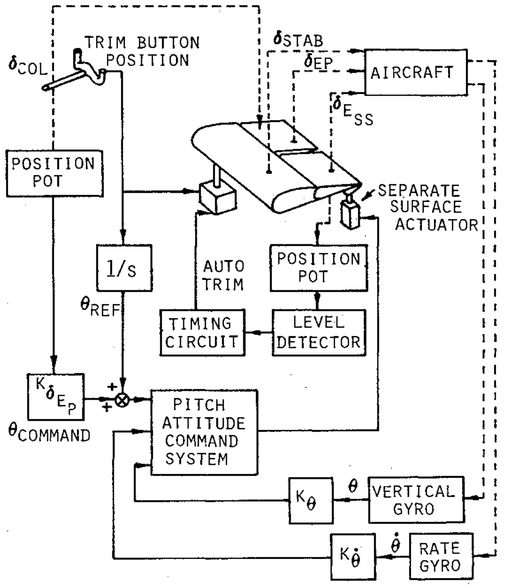

Fig. 9 **Block diagram of longitudinal attitude command trim system.**

Model 99 trim system and the attitude command concept. When the pilot commands a trim change with his wheel-mounted trim button, the horizontal stabilizer changes incidence and a new reference attitude is sent to the attitude command loop. A large "jackknife" angle between the stabilizer and separate surface elevator can result from a trim input. This represents a potentially hazardous mistrim condition in the event of a soft failure or disconnect of the separate elevator. To minimize this hazard, an autotrim loop was added to the longitudinal system. The autotrim drives the horizontal stabilizer through a limited authority secondary trim motor to reduce any jackknife angle to zero.

There are currently no generally accepted criteria for evaluating attitude command systems. Therefore, it was necessary to investigate the pilot acceptance of the system with a piloted simulation conducted at K.U. The Model 99 equations of motion were solved on a set of analog-hybrid computers, and the Iron Bird provided a perfect simulation of the separate surfaces and actuators. The pilot evaluated the system from a representative twin engine general aviation aircraft cockpit.

The following system characteristics were of concern: 1) The system should appear to the pilot to operate in a logical and consistent fashion. 2) All aircraft motions should be adequately damped. 3) The relationship between pilot input and resulting aircraft attitude should be satisfactory. 4) The system should resist attitude excursions caused by external disturbances. Based on the piloted simulation, several minor changes were made to the attitude command system and the final feedback gain values were selected. The simulation was also used to develop setup and checkout procedures and to establish baseline system performance for the flight test program.

A fundamental assumption of the separate surface concept is that, through proper design, the requirements for system redundancy may be reduced or eliminated without increased danger of hazardous failures. This assumption is valid provided that any possible separate surface failures are easily controllable and do not result in any unusual attitudes or hazardous flight conditions with reasonable pilot attention. A fault analysis was conducted to evaluate the consequences of separate surface failures and assess the effects of these failures on the safety of flight of the test aircraft. Following were the steps in the fault analysis: 1) All system components were organized into functional blocks. 2) The possible failures of each functional block were considered. 3) The effect of each possible failure on the test aircraft was predicted. 4) Nontrivial failures were simulated with a pilot participating in the simulation. 5) Hazardous failure states were analyzed on a component-by-component basis. 6) Design changes or operating limitations were developed to eliminate hazardous failure possibilities.

On the basis of the fault analysis and simulation it was concluded that the system was sufficiently developed to permit flight test evaluation and demonstration. Beech Aircraft Corp. is currently modifying a Model 99 in preparation for a flight test program to be conducted during the first part of calendar year 1975. This test program will have as its objectives obtaining flight experience with separate surfaces, investigating and demonstrating the attitude command concept, and obtaining a quantative and qualitative evaluation of the system as installed in the test aircraft.

Summary

Many applications of separate surfaces to general aviation aircraft appear feasible. It is hoped that the flight demonstration of the Model 99 system will provide a stimulus to further development. The following significant considerations emerged during the design of the Model 99 system:

1) Proper sizing of separate surfaces is essential to the effectiveness and safety of a stability augmentation system.

2) The minimum required actuator characteristics are quite dependent on the control law and aircraft dynamics. For the Model 99 system, an actuator with a corner frequency of 7 rad/sec or higher was acceptable.

3) Root locus techniques are adequate for preliminary design, but this should be augmented with piloted simulation, including an Iron Bird or good actuator/surface model.

References

[1] Loschke, P.C., Barber, M.R., Jarvis, C.R., and Enevoldsen, E.K., "Flight Evaluations of the Effect of Advanced Control Systems and Displays on the Handling Qualities of a General Aviation Airplane," Paper 720316, presented at the SAE Business Aircraft Meeting, Wichita, Kan., March 1972.

[2] Collins, D.J. and Bolton, W.R., "A Separate Surface Stability Augmentation System for a General Aviation Airplane," Doctor of Engineering Report, University of Kansas, Apri. 1974, Lawrence, Kan.

[3] Hoak, D.E., Finck, R.D., Ellison, D.E., and Malthan, L.V., "USAF Stability and Control DATCOM," 1968 ed., Flight Control Div.. Air Force Flight Dynamics Lab., Wright-Patterson AFB, Ohio.

[4] Roskam, J., "Flight Test Results of a Separate Surface Wing-Leveling System," Paper 740369 presented at SAE Business Aircraft Meeting, Wichita, Kan., April 1974.

[5] MIL F-8785B (ASG), "Military Specification: Flying Qualities of Piloted Airplanes," Aug. 1969.

[6] Henry, S.A., "Some Methods for Analyzing Aircraft with Linear Automatic Control Systems," Ph.D. dissertation, University of Kansas, Feb. 1974, Lawrence, Kan.