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NASA B737 FLIGHT TEST RESULTS OF THE TOTAL ENERGY CONTROL SYSTEM

by K. R. Bruce,* J. R. Kelly,** L. H. Person, Jr.**

Abstract

An integrated autopilot/autothrottle, namely the Total Energy Control System (TECS), was test flown on the NASA Langley Transport System Research Vehicle (TSRV), a highly modified Boeing B737. The system was developed using principles of total energy in which the total kinetic and potential energy of the airplane was controlled by the throttles, and the energy distribution was controlled by the elevator.

TECS integrates all the control functions of a conventional pitch autopilot and autothrottle into a single generalized control concept. This provides decoupled flightpath and maneuver control and a coordinated throttle response for all maneuvers. The mode hierarchy was established to preclude exceeding airplane safety and performance limits.

Flight test of TECS took place in September 1985 at NASA Langley in a series of five flights over a three-week period. Most of the original flight test plan was completed in the first three flights, and the system did not exhibit any instabilities or design problems that required gain adjustment in flight.

Nomenclature

Symbols

D	drag
E	total energy of system
$\dot{E}_{D_E}$	energy rate distribution error
$\dot{E}_S$	specific total energy rate
$\dot{E}_{S_E}$	total energy rate error
g	acceleration due to gravity
h	altitude
$\dot{h}$	altitude rate
K_{EI}, K_{EP}, K_{TI}, K_{TP}	gain constants
K_{GEPS}	switched gain
s	Laplace operator
T_{REQ}	thrust required
V	airspeed
V_{STALL}	stall speed
$\tilde{V}$	filtered airspeed
$\dot{V}$	rate of change of airspeed
$\dot{V}_{CMAX}$	maximum acceleration command
$\dot{V}_{CMIN}$	minimum acceleration command
$\dot{V}_E$	rate of change of airspeed error
$\dot{V}_{MAX}$	maximum acceleration
W	airplane weight
γ	flightpath angle
γ_C	flightpath angle command
γ_E	flightpath angle error
δ_{E_C}	change in elevator command
δ_{E_T}	change in throttle command
τ_E	time constant of energy rate loop
τ_D	time constant of energy rate distribution loop

Acronyms

AFD	aft flight deck
ALT HOLD	altitude hold mode
ALT SEL	altitude sel mode
AOA	angle of attack
CAS	calibrated airspeed
CMP	control mode panel
DAS	data acquisition system
DATAC	Digital Autonomous Terminal Access Communication System
DME	distance measuring equipment
EADI	electronic attitude display indicator
EPR	engine pressure ratio
FMS	flight management system
FPA	flightpath angle
FPA SEL	flightpath angle select mode
GA	go-around mode
GS	glideslope capture and tracking mode
HOR PATH	horizontal path mode
LRU	line replaceable unit
NCDU	navigation control and display unit
ND	navigation display
PFD	primary flight display
PMC	panel mounted controller
RFD	research flight deck
TECS	Total Energy Control System
TKA SEL	track angle select mode
TSRV	Transport Systems Research Vehicle
VEL-CWS	velocity vector control wheel steering mode

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Introduction

In 1979 NASA funded Boeing to begin the conceptual development of a fully integrated automatic flightpath and speed control system. The work was carried out under NASA contracts NAS1-14880 (1979-1980) and NAS1-16300 (1980-1981). Detailed design and simulator implementation was carried out under Boeing IR&D funding from 1979 to 1982. The outcome of this work was the Total Energy Control System (TECS).

Following successful detailed simulator development of TECS at Boeing, NASA awarded a contract (NAS1-17509) in 1983 for the flight test of TECS on NASA Langley Transport Systems Research Vehicle (TSRV), a highly modified Boeing B737-100.

Flight test of TECS took place in September 1985 at NASA Langley in a series of five flights over a three-week period. Most of the original flight test plan was completed in the first three flights. The final two flights were demonstration flights of TECS.

This paper reviews the basic concept of TECS, discusses the vehicle and system used for the flight test program, and examines the performance of TECS. The results presented concentrate on the unusual aspects of TECS and highlight performance in nonlinear operation, once throttle limiting has occurred.

Basic Concepts of TECS

The basic concepts of TECS are discussed in References 1-3. However, a review of the design philosophy and the theoretical concept is presented in this section.

The work of developing an integrated autopilot/autothrottle was originally initiated to solve the problems identified with conventional uncoupled autopilots and autothrottles, for example:

1. Cross coupling errors in speed and altitude occur when maneuvering due to the design of autopilots and autothrottles as single input/single output control systems. For example, a speed change cannot be accomplished by a change in throttle setting only, but must be accomplished by an elevator retrim if altitude is to be maintained. Conversely, a flightpath angle (FPA) change cannot be achieved by an elevator deflection, but must be coordinated with a change in throttle setting.
2. Autopilot, autothrottle, and flight management systems (FMS) control laws have developed over a long period of time, and this has led to duplication of function in the autopilot and FMS computer.

These problems led to a general design philosophy for TECS:

1. Design the system as a multi-input/multi-output system.
2. Design with a generalized inner loop structure and design the outer loop functions to interface with the common inner loop, thus minimizing software duplication.
3. Provide underspeed and overspeed protection for all modes.

This philosophy integrates the conventional pitch and speed control functions into a single control system, which facilitates the replacement of the autopilot and autothrottle found on current airplanes by a single autoflight line replaceable unit (LRU).

The basic concept of TECS is to control the total energy of the airplane. The total energy of the system can be expressed as the sum of the potential and kinetic energy:

$$E = Wh + \frac{1}{2}\frac{W}{g}V^2 \qquad (1)$$

Where

W = airplane weight
h = altitude
g = acceleration due to gravity
V = airspeed.

The specific energy rate is given by:

$$\dot{E}_s = \dot{h} + \frac{V\dot{V}}{g} \qquad (2)$$

Normalizing by velocity, then:

$$\frac{\dot{E}_s}{V} = \frac{\dot{h}}{V} + \frac{\dot{V}}{g} = \gamma + \frac{\dot{V}}{g} \qquad (3)$$

Where γ = flightpath angle.

From the equations of motion along the flightpath, the thrust required to maneuver is:

$$T_{req} = W\left(\gamma + \frac{\dot{V}}{g}\right) + D \qquad (4)$$

Where D = airplane drag.

Assuming that drag variation is slow, equations (3) and (4) show that the engine thrust required to maneuver is proportional to the specific energy rate of the system. Alternately, it can be stated that the throttles control the rate at which energy can be added to or deleted from the system.

In response to speed or flightpath changes, a control law can be developed that uses the throttles to drive the total energy rate error to zero.

$$\delta_{T_C} = \left(K_{TP} + \frac{K_{TI}}{S}\right)\frac{\dot{E}_{S_E}}{V} \qquad (5)$$

Where

$$\frac{\dot{E}_{S_E}}{V} = \gamma_E + \frac{\dot{V}_E}{g} \qquad (5)$$

This control law uses proportional plus integral control to reduce the total energy error to zero with a first-order time constant, $\tau_E = K_{TP}/K_{TI}$.

However, achieving a speed maneuver without flightpath perturbation, or vice versa, requires coordinated elevator and thrust inputs. An energy rate distribution error $\dot{E}_{DE}$ can still exist, for example, too high a FPA and too low an acceleration. Correction of the energy rate distribution error can be accomplished by feeding back the difference of the acceleration error term $\dot{V}_E/g$ and the FPA error γ_E.

Using proportional plus integral control, the elevator control is:

$$\delta_{E_C} = \left(K_{EP} + \frac{K_{EI}}{S}\right)\left(\frac{\dot{V}_E}{g} - \gamma_E\right) \qquad (6)$$

Where K_{EP}, K_{EI} = elevator proportional and integral gains, respectively.

This control law calls for the use of the elevator to redistribute the energy rate error $\dot{E}_{D_E}$ equally between the FPA and acceleration. The response has a first-order time constant $\gamma_D = K_{EP}/K_{EI}$. This concept is shown in Figure 1.

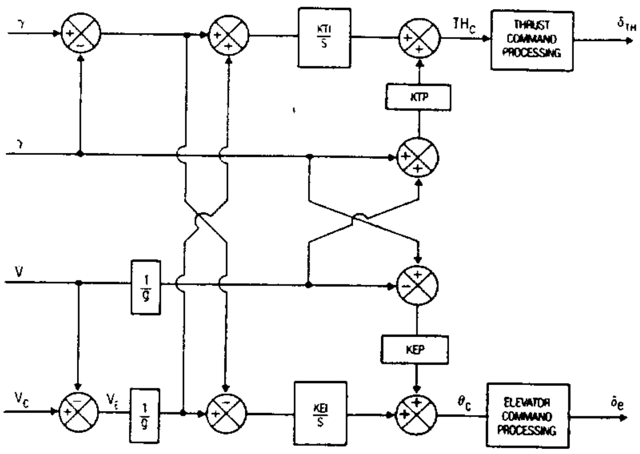

Figure 1. Total Energy Control System Concept

To ensure a coordinated response to both speed and FPA changes, the total energy rate error and the energy rate distribution error must go to zero simultaneously. This requires that ideally the dynamic response of equations (5) and (6) should be identical (i.e., $\tau_E = \tau_D$, and $K_{TI} = K_{EI}$).

In addition, the thrust and pitch response are matched by designing engine and pitch inner loops to minimize variations due to the engine or aerodynamics.

The engine loop is designed to produce the net thrust at all flight conditions. This is achieved by conversion of the net thrust command produced by the control law to a command in terms of the engine pressure ratio (EPR) and closing a feedback loop around the engine using this variable. Software limiting is provided to ensure that neither throttle nor EPR limits are exceeded.

The short period pitch dynamics is stabilized in a conventional manner by the feedback of pitch and pitch rate. The gains were selected to match the thrust dynamics. The variable elevator effectiveness is compensated for by gain scheduling the elevator command as a function of dynamic pressure.

An important aspect of the overall TECS design is the use of a common inner loop for each mode of the autopilot (fig. 2). By generating a common flightpath error signal (γ_E), irrespective of which autopilot mode is engaged, software duplication is minimized and system response is consistent. To implement the FPA mode, for example, the (γ_E) signal is generated by differencing a FPA command (γ_C) from the control mode panel with a γ signal computed from height rate ($\dot{h}$) and filtered velocity (V).

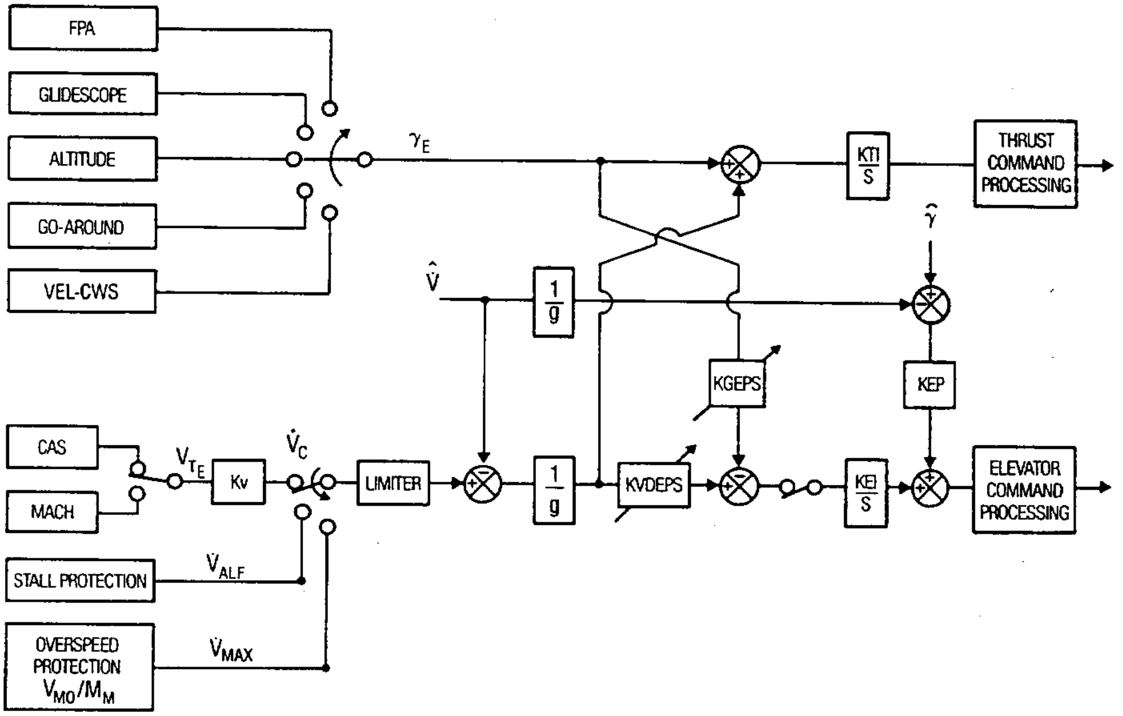

Figure 2. Simplified TECS Implementation

For control of altitude and glideslope, outer loop control is added to generate the normalized γ_C signals and provide exponential capture of the desired altitude or glideslope. All inputs, except for the velocity vector control wheel steering mode (VEL-CWS), are rate limited to provided 0.1 g maximum normal acceleration during maneuvers.

The speed modes, calibrated airspeed (CAS) and Mach, both use outer loop control, similar to the altitude and glideslope modes, to provide exponential capture of the parameter. An acceleration command ($\dot{V}_C$) drives the inner loops.

The control modes are divided into speed or path priority so that, when throttle limiting occurs, either speed or flightpath has priority and control of that parameter is maintained. The other parameter goes open loop and is not controlled. The mode logic of TECS is set up so that FPA, altitude, and go-around mode have speed priority, while glideslope and VEL-CWS mode have path priority.

Control of the system, while throttle limiting, is an important aspect of TECS that required significant development on a nonlinear simulator to achieve an implementation with minimum software that provided accurate control and was consistent with the speed/path priority for each mode. This implementation is discussed in more detail in the later section that covers the flight test results.

The result of the TECS design is a fully integrated system that has predictable consistent performance in all modes. Duplication of software has been minimized by maintaining a common inner loop structure.

Architectural Features of the System

The TECS flight tests were conducted on NASA Langley TSRV, which is a highly modified Boeing 737-100 aircraft (fig. 3) designed to investigate advanced navigation, guidance, control, and display concepts applicable to the emerging National Airspace System. In this aircraft, the entire experimental flight management system (i.e., all the navigation, guidance, and control functions, and the primary pilot displays) are under software control and can be reprogrammed to suit the requirements of a particular experiment.

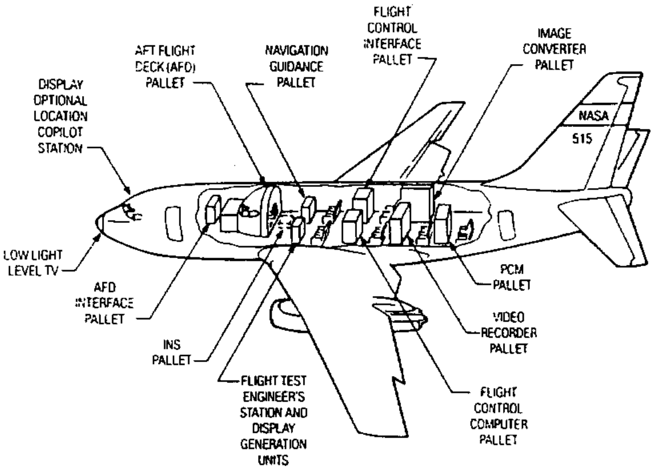

Figure 3. NASA Langley TSRV Showing Internal Arrangements

The TECS flight tests employed the full-up test configuration in which the aircraft is flown from a research flight deck (RFD) mounted in the cabin of the aircraft and referred to in this paper as the aft flight deck (AFD). The AFD features programmable electronic primary flight displays (PFDs), navigation displays (NDs), a navigation, control, and display unit (NCDU), a glare-shield mounted control mode panel (CMP), and panel-mounted controllers (PMC) that take the place of conventional column and wheel controls. The CMP (fig. 4) was modified for these tests by replacing selected baseline switch legends with ones corresponding to the TECS modes.

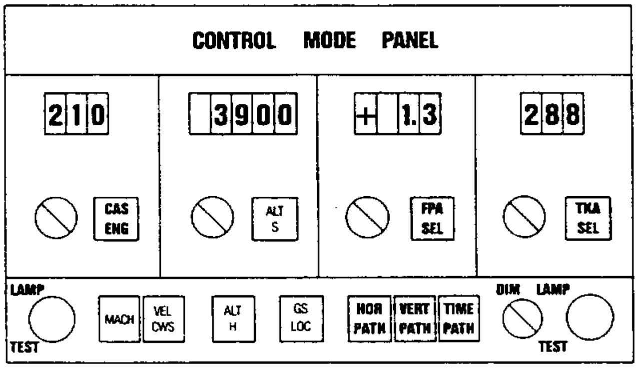

Figure 4. TSRV/TECS Control Mode Panel

Figure 5 is a simplified block diagram showing the arrangement of the principal components of the research system. The system is built around two Norden digital flight computers that are militarized versions of the general purpose PDP 11/70 computer. Both computers are interfaced to the AFD and an extensive array of sensors by a global data bus known as the Digital Autonomous Terminal Access Communication (DATAC) system. This installation is the first practical application of DATAC, a high-speed (1 MHz) multitransmitter/receiver data bus that requires only a single twisted wire pair to link all components on the bus. In the TSRV, two DATAC busses are actually used: one for navigation, guidance, and control functions and the other for the programmable display system. A data acquisition system (DAS) is also coupled to the DATAC bus and is set up to record approximately 540 data channels at 20 samples per second, with selected channels at 100 samples per second.

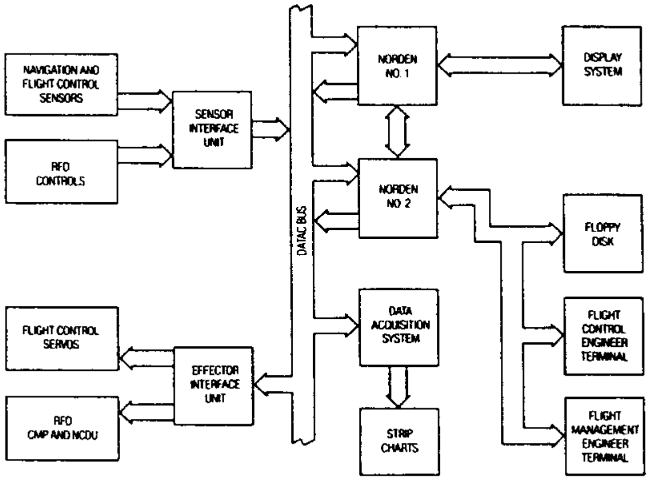

Figure 5. Research System Architecture

The TECS algorithms are programmed into the Norden computers via floppy disk and replace the pitch control and throttle control algorithms of the baseline software. The system, as flown on the TSRV airplane, consists of the following longitudinal modes:

1. Velocity vector control wheel steering (VEL-CWS)
2. Glideslope capture and tracking (GS)
3. Flightpath angle select (FPA SEL)
4. Altitude select and hold (ALT S, ALT H)
5. Go-around (GA)

The system longitudinal modes can be flown in either CAS or Mach speed modes.

AL-5

The TECS software is integrated with the baseline lateral modes to give default mode pairing. Engagement of a longitudinal mode, for example, would result in the engagement of a corresponding mode in the lateral axis, or vice versa (fig. 6). On power up of the TECS system, the system is default in VEL-CWS and CAS modes. Engagement of FPA SEL, ALT H, ALT S, or GA modes gives track angle select (TKA SEL) in the lateral axis.

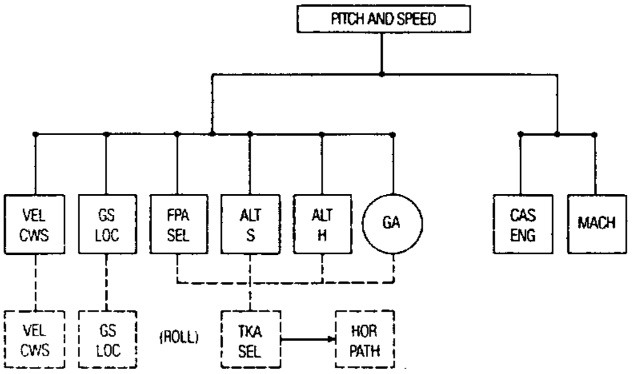

Figure 6. TECS Control Modes

The lateral VEL-CWS mode incorporates roll rate command/attitude hold for maneuvering flight and track angle hold for nonmanuevering flight.

In integrating TECS with the baseline, certain selected navigation, guidance, and lateral control functions were retained. These functions included dual distance measuring equipment (DME), aided inertial navigation, and a horizontal path (HOR PATH) guidance mode in which the flightpaths can be selected by the pilot from a prestored data base or can be constructed in real-time using the NCDU. The baseline vertical path and time control modes were not enabled during these tests.

Flight Test Results

Selected examples have been taken from the flight test results to illustrate the performance and operation of the system and highlight the unique aspects of the system.

FPA/CAS Modes

As discussed, each mode of the autopilot is prioritized to control either speed or path when throttle limiting occurs. In FPA mode, the strategy is simple: speed control has priority. Hence, on dialing in a large positive FPA, the throttle will reach the forward limit and stop (fig. 7). The system will now stop controlling FPA; the throttle integrator is limited and the crossfeed between FPA and elevator is cut (i.e., the gain K_{GEPS} (fig. 2) is set to zero).

The system controls speed through elevator. With the throttle at the forward limit, any energy not required to maintain speed is available to increase the FPA and, hence, the climb rate. Figure 7 shows that in steady state climb at this flight condition the airplane can maintain about 6-deg FPA at 200 kn, a climb rate of about 40 ft/s. Maximum speed deviation during the maneuver was about 2 kn.

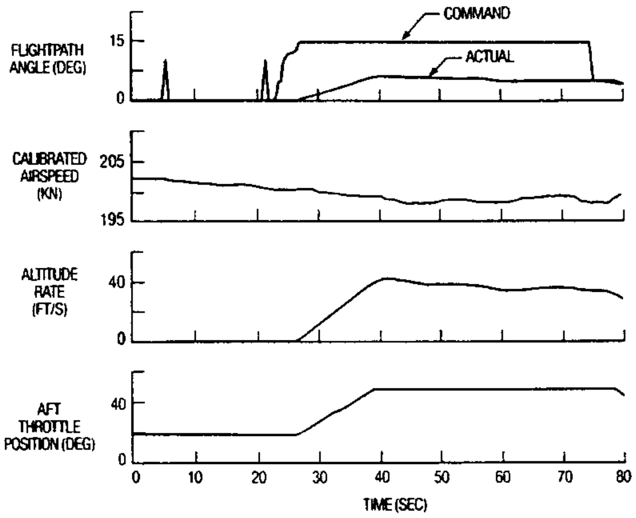

Figure 7. FPA Mode

In the situation of a large speed change, for instance a 100-kn increase as shown in Figure 8, when in FPA mode (or altitude hold mode), the large initial velocity error drives the throttle to the forward limit. When the throttle limits, the path error signal (γ_E) into the elevator path is cut, as described, by setting K_{GEPS} to zero. The limiter in the V_C signal path (fig. 2) is reduced to:

$$\dot{V}_{MAX} = \dot{V} - \gamma_E g \qquad (7)$$

Since γ_E is small in this maneuver, $\dot{V}_{MAX} = \dot{V}$ is the nominal value of the limit, that is, the acceleration maintains at the level achieved just prior to limiting.

Any errors in γ vary the value of the limiter. Considering equation (7) and Figure 2, a positive γ_E results in a negative V_E that gives a negative elevator signal (i.e., the airplane pitches up to null the γ_E signal). The resultant effect is that the system varies the longitudinal acceleration during the speed change to maintain path tracking.

As the capture speed is approached, the acceleration command decreases below the limiter value, the throttle comes off the limit, the crossfeed is restored, and the target speed is captured exponentially. During this maneuver, altitude error was less than 20 ft and normal acceleration was less than 0.1 g.

Figure 8 also shows the comparable performance for a large speed decrease when the throttles reach the idle limit.

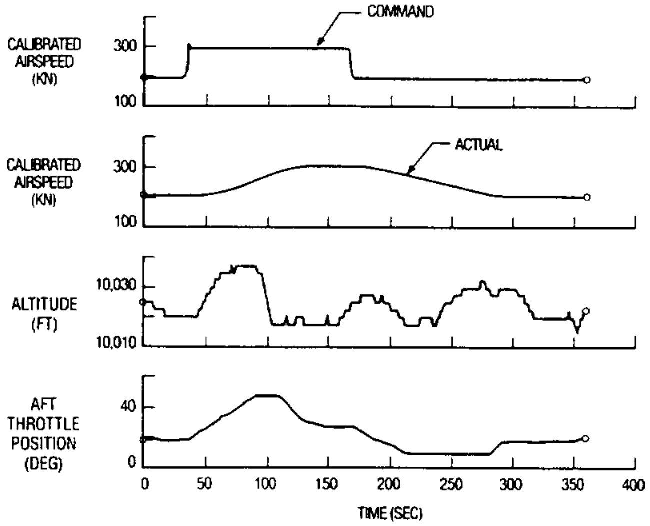

Figure 8. Airspeed Change

Altitude Select and Hold Mode

The TECS control mode panel (fig. 4) allows a target altitude to be dialed in the altitude window. The system will attempt only to capture that altitude when the altitude select button is pressed. As described, in altitude (or FPA) mode, speed has priority; for large altitude changes, the throttles will limit, the system will maintain control of speed, and the remaining available energy will be used to achieve the maximum climb rate possible. If, during this maneuver, an increase in speed is desired, the limit logic computes the total energy rate available and splits the energy so that 50% is used for climb and 50% is used for acceleration. This is achieved by setting the $\dot{V}_C$ signal path limiter (fig. 2) to 50% of the total available energy (i.e., $0.5\ (\dot{V} + \gamma_g)$).

This ratio is readily adjustable by changing one gain in the software if it is determined by pilot evaluation that priority should be given to achieving speed or altitude capture first.

An example of this maneuver is shown in Figure 9. The airplane was climbing to 10,000 ft altitude and increasing speed to 270 kn. The energy is split evenly between climbing and accelerating. In this example, the acceleration is approximately 2.5 ft/s^2, which in energy terms corresponds to a γ of about 0.08 rad if the split is even. Once the reference speed of 270 kn is captured, the climb rate doubles from about 35 ft/s to a maximum of 70 ft/s.

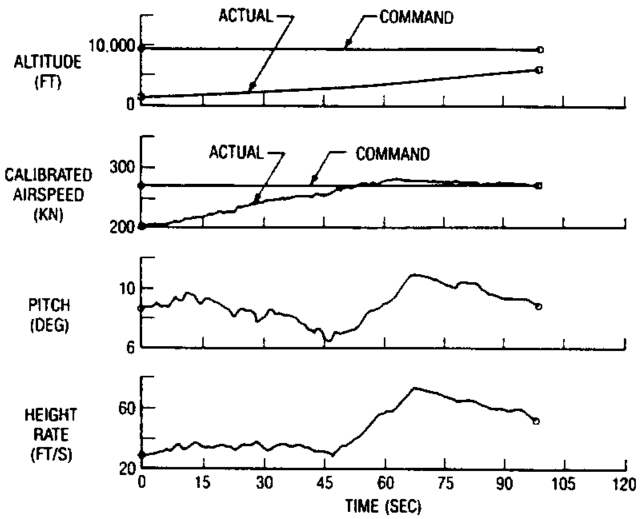

Figure 9. Climb Out

During descent maneuver, speed has priority and all the energy rate is applied to decelerating the airplane. A speed change during descent will cause the airplane to level out, capture the new speed, and then continue the descent to the selected altitude.

Underspeed and Overspeed Protection

Underspeed and overspeed protection are priority control modes that switch in automatically, if required, irrespective of whether the mode engaged has speed or path priority.

In the underspeed protection mode, the actual wing angle of attack is compared with a reference alpha. The reference alpha value corresponds to 1.3 V_{STALL} for each flap setting. The error signal is converted to a normalized acceleration command ($\dot{V}_{CMIN}$) that is computed continuously. Similarly, for the overspeed mode, a normalized acceleration $\dot{V}_{CMAX}$ is computed continuously from the velocity error between the actual airspeed and the overspeed reference value.

The mode engages underspeed protection automatically when

$$\dot{V}_{CMIN} > \dot{V}_c \qquad (8)$$

and engages overspeed protection when

$$\dot{V}_{CMAX} < \dot{V}_c \qquad (9)$$

Two examples of the operation of the underspeed protection mode for angle of attack (AOA) limiting are shown in Figures 10 and 11. Figure 10 illustrates the situation of dialing the speed command to a very low value. The airplane slows down and when $\dot{V}_{CMIN} = \dot{V}_c$ the mode switches in a transient free manner and controls to the reference alpha. At flaps 0 deg, this corresponded to about 180 kn. As the flaps were extended to flaps 40 deg, speed decreases as the system controls to the new reference. Altitude deviation during the maneuver was negligible.

Figure 11 shows a nonstandard situation in which speed has been dialed down and flaps rapidly extended to 40 deg. The maneuver was accomplished safely with little altitude deviation although considerable pitch down was experienced in the airplane.

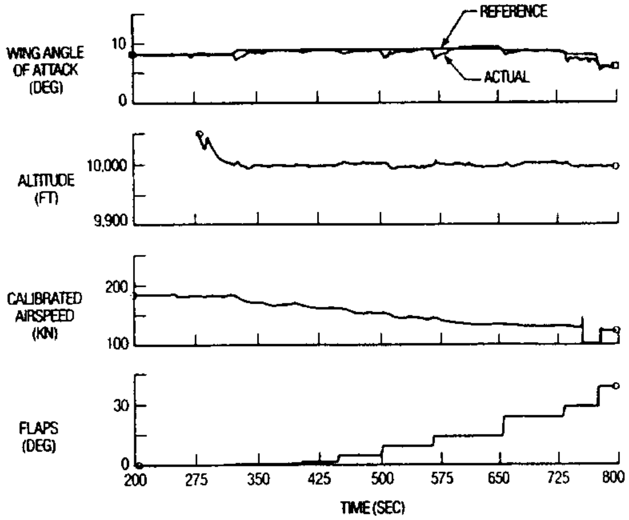

Figure 10. Underspeed Protection Mode

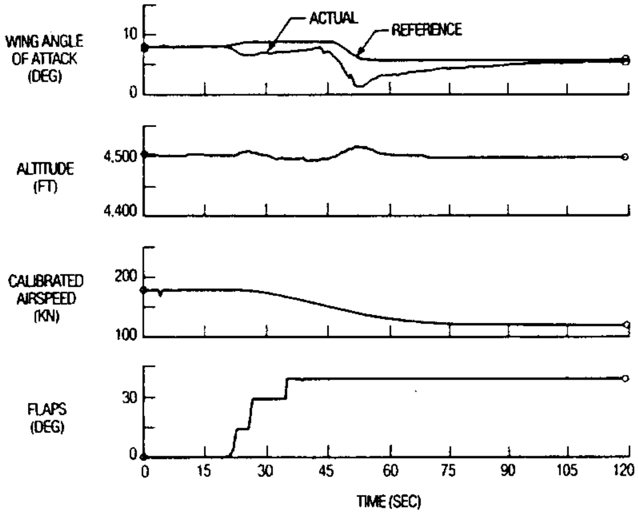

Figure 11. Underspeed Mode With Rapid Flap Extension

Energy Exchange Maneuver

For this maneuver, the increase in kinetic energy has been set equal to the decrease in potential energy (decrease in height) (fig. 12). This is not a normal maneuver for a pilot. However, it does demonstrate very clearly the coordination between throttle and elevator and shows the linear performance of TECS. In this maneuver, the airplane has lost 600 ft of altitude and gained 20 kn in airspeed. The energy trade has been accomplished by using the elevator alone, achieving a maximum altitude rate of about 40 ft/s. Aft flight deck throttle motion was a maximum of about 0.5 deg.

A key feature of TECS is the similar outer loop bandwidth of the altitude and speed control loops. This is seen to be almost identical and has a time constant of about 12 sec (set by the outer loop gains).

Normal acceleration during the maneuver was always below the design constraints of 0.1 g (3.2 ft/s).

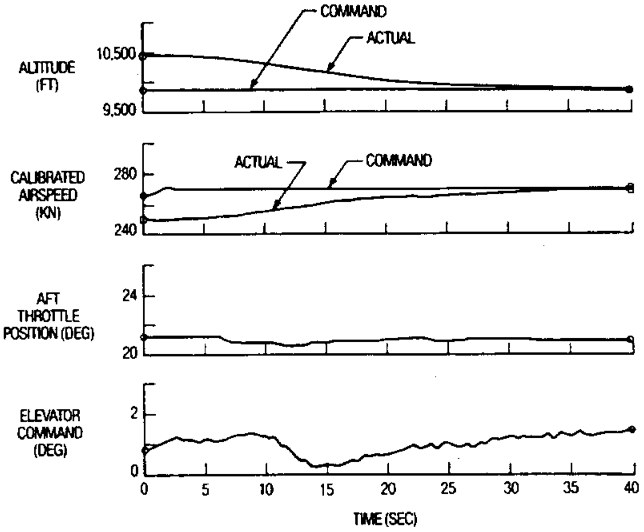

Figure 12. Energy Change (KE=PE)

Velocity Vector Control Wheel Steering (VEL-CWS) Mode

The VEL-CWS mode is a manual flying mode with control augmentation, which significantly reduces the pilot workload when flying a path defined in inertial space.

In this mode, a column deflection commands a rate of change of FPA. Figure 13 shows the ideal response of γ for a step column input. It can be seen that the γ response lags the command (γ_c) by a fixed amount τ_γ. This value was a compromise between obtaining the fastest time possible and obtaining consistency in response over the whole flight regime and was adjusted to about 1 sec. The VEL-CWS control law was added to the basic TECS inner loop structure by using command feedforward terms to quicken the response. Original attempts to use the γ_c path of the TECS inner loop structure resulted in too sluggish a response. The final configuration employed a feedforward integral path to the throttles, as well as proportional and integral paths to the elevator.

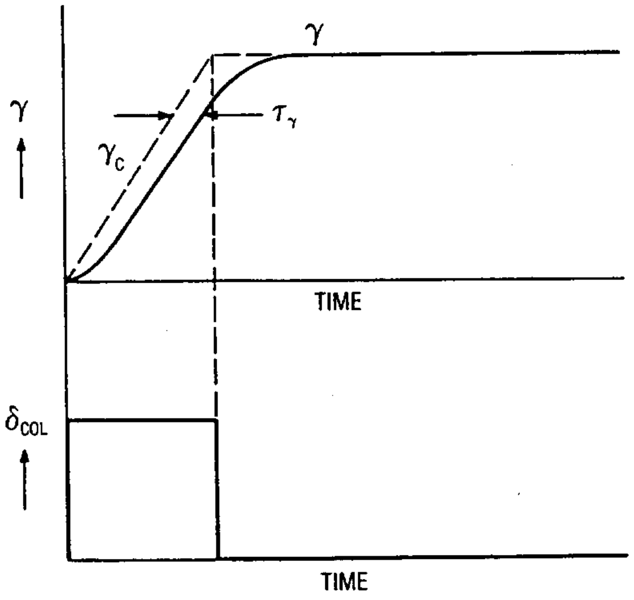

Figure 13. Desired Gamma Response for Column Inputs

The implementation of this mode is shown in Figure 14. The control column deflection signal is scheduled with 1/V to provide a constant deflection per g ratio over the flight regime. The electronic attitude display indicator (EADI) on board the airplane displays both γ and γ commands, and this combination of display and control law has received very favorable pilot reaction in reducing pilot workload when flying manually. For example, if the pilot is flying a path in space or a glideslope, he can set the command wedge or the display at the reference angle and stay out of the loop while the control law does the work. This is particularly true in turbulent conditions in which no display of the γ command encourages the pilot to enter the control loop and, hence, will dramatically increase the workload.

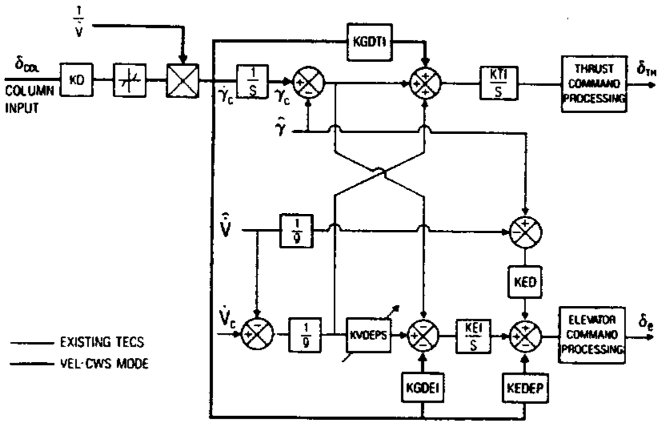

Figure 14. Incorporation of VEL-CWS in TECS

Figure 15 shows operation of the VEL-CWS mode for a 700-ft flight level change. The maneuver was executed without overshoot of γ or altitude. Speed was a maximum of about 2 kn underspeed during the descent. For the VEL-CWS mode, acceleration limiting is not provided, on the rationale that the pilot may want to pull high g's in an emergency situation. For this example, vertical acceleration peaked at 5 ft/s^2.

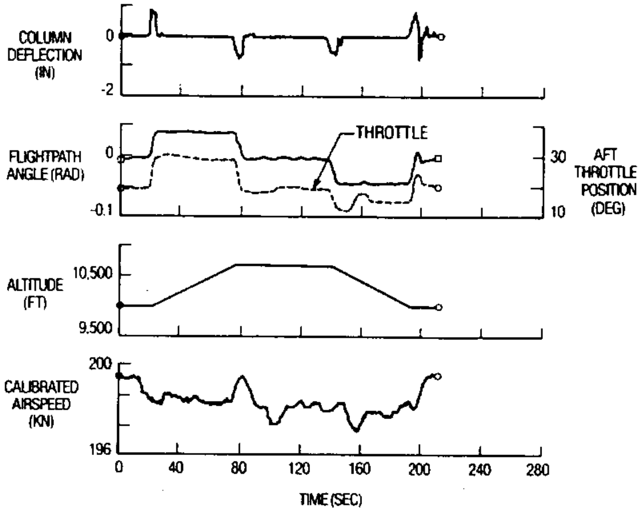

Figure 15. Velocity Vector CWS

Figure 16 shows a maximum column deflection input with throttle limiting. The FPA initially has priority and the command is reached. However, speed bleeds off rapidly and the underspeed protection mode switches in, γ then decreases, despite additional column positive inputs until the minimum speed is reached (about 178 kn, for flaps 0 deg) and the maximum γ commensurate with the minimum speed is achieved. A negative column input decreases γ and the airplane returns to the reference speed of 200 kn.

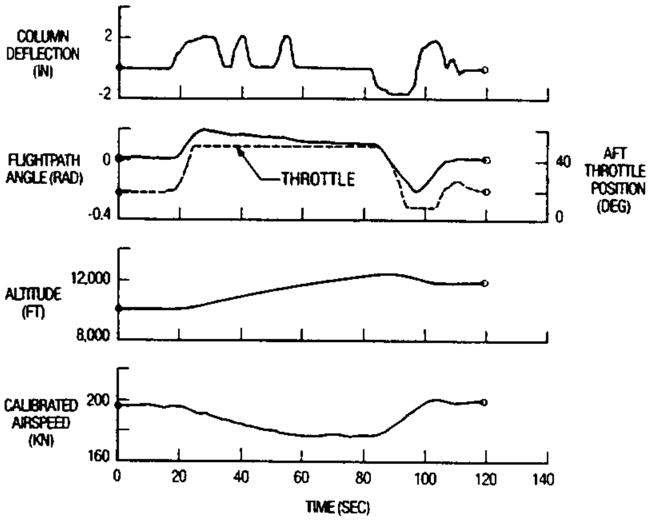

Figure 16. Velocity Vector CWS

Approach and Go-Around

The full-time underspeed protection, discussed above, can be used during approach to reduce the pilot workload. Figure 17 shows an approach and go-around situation. The airplane approached the glideslope in altitude hold mode at 3000 ft, flaps 15 deg, gear down. The glideslope error signal shows the capture and the path tracking capability. On capture of the glideslope, the command speed was dialed from 150 kn to a low value and the flaps were extended from 15 deg to 40 deg. Speed was reduced to V_{ref} commensurate with the flap setting. For safety reasons, the command speed was dialed up to 120 kn prior to go-around.

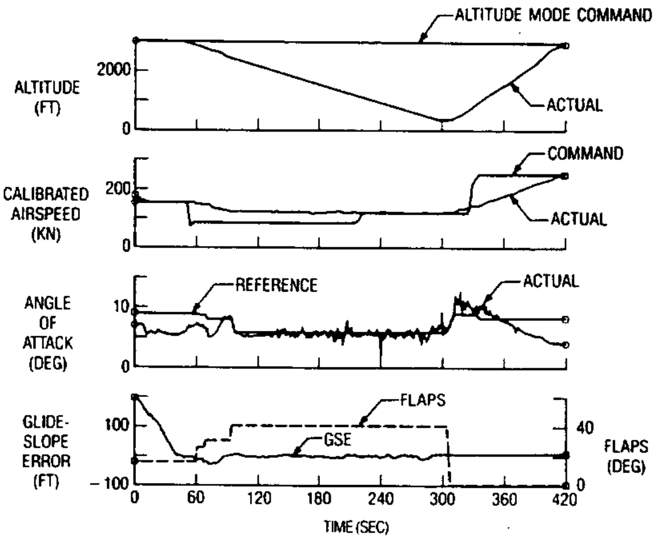

Figure 17. Approach and Go-Around

The TECS system did not include a flare control law. A system was developed, but it did not undergo the exhaustive development and testing necessary for a flare control law. For this series of tests, go-around was initiated at 300 ft. On go-around, the control law commands a large FPA. This gives large elevator and throttle commands that cause the airplane to pitch up and climb at the maximum rate attainable while maintaining speed.

During climb out, the reference speed was dialed up to 250 kn. However, because of overspeed protection set to the placard value at each flap setting, speed will increase only to the placard value until the flaps are retracted.

The reference altitude remained at 3000 ft during the entire maneuver. In go-around mode, the altitude mode is armed; hence, as the airplane climbed out, the capture criteria was satisfied and the airplane exponentially captured the reference altitude of 3000 ft.

Pilot Reaction to Flying the TSRV With TECS

Pilot reaction to flying the TSRV with TECS was very favorable. Explanation of the TECS concept and philosophy to pilots was very important so that the operation of TECS was predictable and consistent in flight.

A major difference from conventional systems is the full-time autothrottle. Traditionally, autothrottles have been heavily criticized for excessive activity and unpredictable or counterproductive motion in maneuvers. TECS solves that problem and produces an autothrottle that is predictable and minimizes unnecessary throttle activity, both in situations of simultaneous altitude and speed changes and when flying the VEL-CWS mode. The pilot does not need to switch off the autothrottle and fly manual throttles to achieve satisfactory flying qualities.

With TECS, the mode logic is simple and the mode hierarchy is straightforward so the behavior is predictable in throttle limiting conditions. In all events, limiting prevents stall and overspeed irrespective of the mode or combination of modes.

The strategy adopted during simultaneous speed and altitude changes of splitting energy (50%/50% during climb, 100% into deceleration during descent) is flexible and, although considered the preferred system, can readily be changed by adjusting one gain.

The VEL-CWS mode is the preferred method of flying the airplane during climb out and approach. It allowed the pilot, as opposed to the autopilot, to fly the airplane with great precision and yet greatly reduces the workload. Interception and tracking of the glideslope, even in turbulence, is a simple task.

Conclusions

- The Total Energy Control System was successfully flight tested on the NASA Langley TSRV (B757) in a total of five flights. The system did not exhibit any instabilities or design problems that required gain adjustment in flight. No major problems were encountered during the tests.
- The success of the flight tests validates the extensive use that was made of analysis, simulation, and hot bench checkout to thoroughly develop, check out, and verify the system design prior to flight tests. No system tuning was necessary in flight.
- The integrated autopilot/autothrottle received favorable pilot reaction. The full-time autothrottle inherent in the design was predictable during manuevers and did not exhibit unnecessary throttle activity.
- Performance in all modes was comparable to simulation results. Path tracking was excellent: altitude deviation during large speed changes was less than 20 ft. Speed tracking during manuevers was generally less than 2 kn, although a peak error of 5 kn was noted on certain large altitude changes.
- The velocity vector control wheel steering (VEL-CWS) mode received very favorable pilot reaction because of its consistent performance over the flight regime, the predictable and responsive throttle, and the reduction in workload that the mode allows when carrying out precision tracking tasks.
- TECS has provided NASA with a state-of-the-art integrated autopilot/autothrottle suitable for use with future NASA experiments such as 4D navigation.

References

1. Lambregts, A. A., Vertical Flight Path and Speed Control Autopilot Design Using Total Energy Principles, AIAA Paper 83-2239CP, August 1983.
2. Lambregts, A. A., Operational Aspects of the Integrated Vertical Flight Path and Speed Control System, SAE Paper 831420, October 1983.
3. Lambregts, A. A., Integrated System Design for Flight and Propulsion Control Using Total Energy Principles, AIAA Paper 83-2561, October 1983.