[4]"An Interim Report on the Stability and Control of Tailless Airplanes," Rept. 796, 1944, NACA.

[5]"Canada Weighs Arctic Resources Airlift," *Aviation Week and Space Technology*, Vol. 96, No. 21, May 22 1972, pp. 25–26

[6]Unpublished data on a Lockheed Aircraft Corporation "Span Loader" supplied by Dr. Brent Silver.

[7]Cleveland, F. A., "Size Effects in Conventional Aircraft Design," *Journal of Aircraft*, Vol. 7, No. 6, Nov.–Dec. 1970, pp. 483–512.

[8]Jones, R. T., "Reduction of Wave Drag by Antisymmetric Arrangements of Wings and Bodies," *AIAA Journal*, Vol. 10, No. 2, Feb. 1972, pp. 171–176.

[9]Jones, R. T., "New Design Goals and a New Shape for the SST," *Astronautics and Aeronautics*, Vol. 10, No. 12, Dec. 1972, pp. 66–70.

[10]Bisplinghoff, R. L., Ashley, H., and Halfman, R. L., *Aeroelasticity*, Addison-Wesley, Reading, Mass., 1955.

[11]Bisplinghoff, R. L. and Ashley, H., *Principles of Aeroelasticity*, John Wiley and Sons, New York, 1962.

[12]Etkin, B., *Dynamics of Flight; Stability and Control*, John Wiley and Sons, New York, 1959.

[13]Hancock, G. J., "The Static Aeroelastic Deformation of Slender Configurations, Part I: Some Elementary Concepts of Static Deformation," *The Aeronautical Quarterly*, Vol. XII, Aug. 1961, pp. 293–308.

[14]Hancock, G. J., "The Static Aeroelastic Deformation of Slender Configurations, Part II: Some Calculations on Slender Plate Aircraft, Including Non-linear Aerodynamics," *The Aeronautical Quarterly*, Vol. XII, Nov. 1961, pp. 372–394.

[15]Hancock, G. J., "The Static Aeroelastic Deformation of Slender Configurations, Part III: Static Stability," *The Aeronautical Quarterly*, Vol. XIV, Feb. 1963, pp. 75–104.

[16]Hancock, G. J., "The Static Aeroelastic Deformation of Slender Configurations, Part IV: Manoeuvre Theory, "*The Aeronautical Quarterly*, Vol. XIV, Nov. 1963, pp. 311–330.

[17]Diederich, F. W. and Budiansky, B., "Divergence of Swept Wings," TN 1680, Aug. 1948, NACA.

[18]Graham, L. A., Jones, R. T., and Boltz, F. W., "An Experimental Investigation of an Oblique-Wing and Body Combination at Mach Numbers Between 0.60 and 1.40," TM X-62,207, Dec. 1972, NASA

OCTOBER 1973 J. AIRCRAFT VOL. 10, NO. 10

Control System Design Considerations for a Longitudinally Unstable Supersonic Transport

Lloyd R. Tomlinson*
The Boeing Company, Seattle, Wash.

The greatest challenge facing designers of the USA Supersonic Transport was to achieve a design that was economically competitive with the large subsonic transports. In order to achieve this goal, it was necessary to design a Control Configured Vehicle (CCV) which relied on stability augmentation to meet handling qualities and safety requirements. The result was the achievement of significant gains in structural weight and aerodynamic efficiency, netting substantial improvements in range/payload capability. In the process of developing the controls design, several interesting problems were dealt with. New approaches to safety assurance were necessary. The low frequency structural modes imposed constraints on the amount of airframe instability that could be compensated for by the stability augmentation system. Complex augmentation using speed feedback was necessary for complete stability. The augmentation authority and resolution requirements increased significantly. Such problems as nose wheel taxi loads and control forces to rotate for takeoff took on new significance. It is the object of this paper to discuss these problems for possible benefits to future CCV designs.

Introduction

THE effects of transonic flight were particularly apparent for the USA/SST. Figure 1 shows the greatly expanded flight envelope that was planned for the SST. Figures 2 and 3 present typical variations with Mach number of a few key aerodynamic parameters. In the transonic region, large changes occur in all the aerodynamic characteristics, and as Mach number increases to cruise speed, a great reduction takes place in control effectiveness. The large variations in stability, and the reductions in control effectiveness stems from the redistribution of aerodynamic loads in supersonic flow and from aeroelastic distortions. The shift in aerodynamic center with Mach number (Fig. 3) is seen to be of a magnitude three times greater than the allowable loading range for the center of gravity (c.g.).[1]

One of the most critical tasks in the development of an SST configuration is the achievement of satisfactory longitudinal balance. The final arrangement of the airplane must provide an operational c.g. range that satisfies airline requirements for payload loading flexibility while insuring satisfactory longitudinal stability and control and minimum trim drag. Figure 4 illustrates the SST balance problem. Performance, noise, and structural considerations strongly dictated locating the engines on the trailing edge of the wing. This, however, caused a balance problem which would have required a forward extension of the fuselage to provide acceptable c.g. limits for stability if conventional design procedures had been used. The basic problem was that location of the engine masses on the trailing edge of the wing resulted in the Operating Empty Weight (OEW) c.g. being aft of the desired subsonic operating c.g. range. Normal balance could only be

Presented as AIAA Paper 72-871 at the AIAA Guidance and Control Conference, Stanford, Calif., August 14–16, 1972; submitted October 2, 1972; revision received July 16, 1973.

Index categories: Aircraft Configuration Design; Aircraft Handling, Stability and Control; Aircraft Subsystems Design.

*Specialist Engineer, Flight Controls Technology.

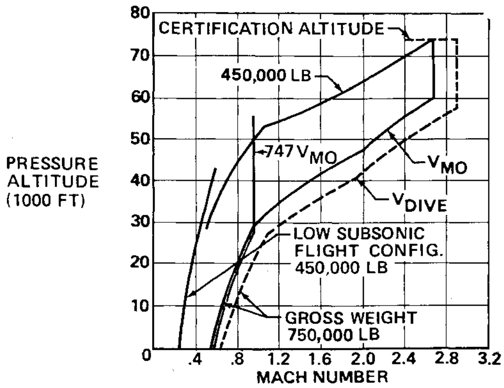

Fig. 1 Operational envelope.

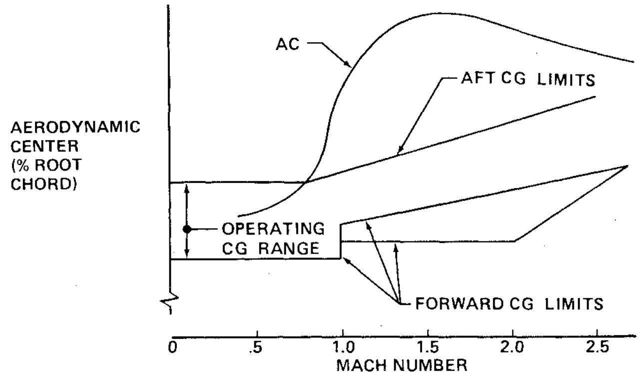

Fig. 3 Mach effects on aerodynamic center.

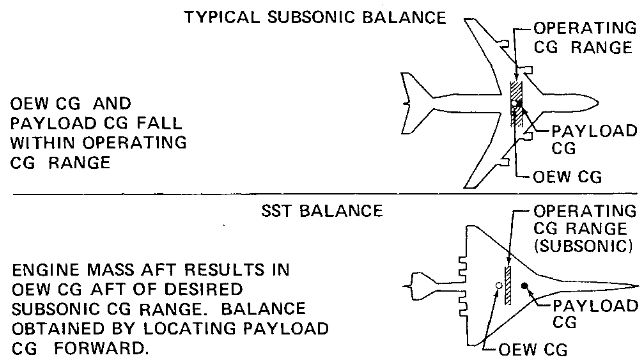

Fig. 4 Longitudinal balance.

obtained by locating the payload forward. In order to shorten the fuselage, save weight, and improve performance, it was elected to locate the c.g. aft of the maneuver neutral point at subsonic speeds and to size the control surfaces to meet control moment requirements rather than stability requirements, thus making the airplane dependent on stability augmentation for acceptable handling characteristics in subsonic flight. The performance benefits resulting from this decision are summarized in Table 1. There were considerable improvements in range/payload, takeoff and landing speed, noise, and field length requirements.

The necessity to minimize weight and tail drag, and the decrease in conventional elevator effectiveness at high Mach conditions, resulted in the selection of a single, moving horizontal stabilizer control surface for both trim and control inputs. A geared elevator was added to the stabilizer to improve surface effectiveness and reduce total surface size. A sketch of the resulting SST configuration is shown in Fig. 5.

Design Philosophy to Optimize Safety

Since satisfactory handling qualities and, hence, safety were dependent on the Stability Augmentation System (SAS), considerable thought was given to the problem of optimizing the functional reliability of the system. The design objective established for the SAS was that the system should provide at least minimum safe augmentation with a functional reliability that approximates the reliability of the basic airframe structure. This means that the probability of ever losing the augmentation function that assured safe control of the airplane to a satisfactory landing was at least extremely remote. Extremely remote failure conditions are those that, although theoretically possible, are not expected to happen in the total lifetime of an SST fleet. In order to meet the extremely remote probability objective and to optimize safety, the concept of a Hardened Stability Augmentation System (Hard SAS or HSAS) was developed for the pitch axis of the SST. The design approach selected for the HSAS was to specify the simplest possible system that could assure at least minimum safe control, to take all reasonable precautions to optimize the reliability of this system during manufacture and service, and to minimize maintenance requirements. Minimum safe handling qualities were defined as requiring a pilot rating of 6.5 or better on the Cooper Scale and by not permitting unstable roots with a time to double amplitude of less than 6 sec.

Normal handling qualities were provided by an outer loop system called an Electric Command and Stability System (ECSS). Use of multiple sensors, gain scheduling, and conventional packaging techniques were permitted in the ECSS to optimize handling qualities and minimize maintenance complications.

HSAS Criteria

The dominant criteria which controlled the HSAS design are listed below:

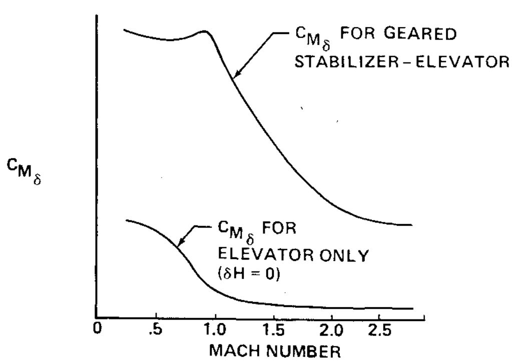

Fig. 2 Longitudinal control effectiveness.

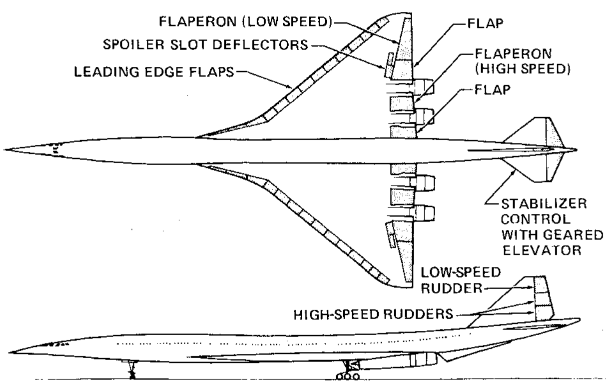

Fig. 5 SST airframe.

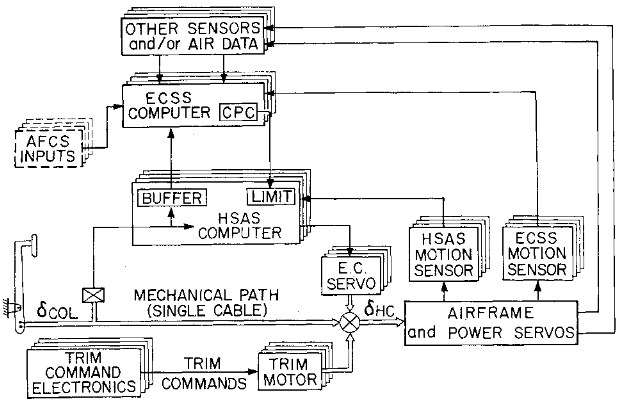

Fig. 6 General layout of SST control system design.

1. The premise that the least complex HSAS would be the most reliable was used to establish the criteria that performance improvement techniques such as gain scheduling or multiple sensor inputs that were unnecessary to meet the minimum safe handling qualities requirements were not allowed.
2. Only service proven components were permitted in the HSAS design, and rigid requirements on selection, derating, acceptance testing, and burn-in were established.
3. Redundant channel design was allowed to meet the reliability goals. Early reliability studies showed that four channel redundancy was required to meet the reliability goals; therefore the system had to be fail operational for the first two channel failures. The system was also required to be fail passive on third channel failure. This requirement was imposed so that safe control could be provided by a nonredundant mechanical backup control system.
4. Maximum isolation between the redundant channels was required so that the possibility of unpredictable failures propagating between the channels was minimized. Electronic signal selection (voting) was not allowed in HSAS.
5. No single point failures were allowed in the HSAS Control path except for unavoidable single jam points in the mechanical control to the single surface. The unavoidable single jam points were provided with the best possible jam protection.
6. HSAS packaging criteria was established to minimize the probability of unnecessary removal of any HSAS component, and to minimize the possibility of damage through mishandling.
7. Maintenance requirements on HSAS were minimized.
8. The interface of the HSAS with other nonessential systems was minimized to lessen the possibility of failures from the nonessential systems propagating into HSAS.
9. Failures within interfacing systems that were not essential to minimum safe control were isolated from the HSAS by channel processing circuits (CPC's)† and by signal limiters that prevented any multichannel failure condition from exceeding the pilot's ability to maintain control of the airplane with the HSAS operating.

$$\begin{bmatrix} Sm - X_u & \left[-SX_{\dot\alpha} - X_\alpha\right] & \left[(mu_0\alpha_0 - X_Q)S + mg\cos\theta_0\right] \\ \frac{2L_0}{U_0} - Z_{\hat u} & \left[S(mu_0 - Z_{\dot\alpha}) - Z_\alpha\right] & \left[(-mu_0 - Z_Q)S + mg\sin\theta_0\right] \\ -(M_u - \underline{Z_{\hat u}\bar c K_{c.g.}}) & \begin{bmatrix} S(M_{\dot\alpha} - \underline{Z_{\dot\alpha}\bar c K_{c.g.}}) \\ -(M_\alpha - \underline{Z_\alpha \bar c K_{c.g.}}) \end{bmatrix} & \left[I_{yy}S^2 - (M_Q - \underline{Z_Q\bar c K_{c.g.}})S\right] \end{bmatrix} \begin{bmatrix} \Delta u \\ \Delta\alpha \\ \Delta\theta \end{bmatrix} = \begin{bmatrix} X_H \\ Z_H \\ M_H - \underline{Z_H \bar c K_{c.g.}} \end{bmatrix} \delta_H$$

WHERE $K_{c.g.} = \dfrac{X_{c.g.} - X_{ref}}{\bar c}$

$\bar c$ = MEAN AERODYNAMIC CHORD OR REFERENCE CHORD.
OTHER DERIVATIVES ARE NORMAL AERO DERIVATIVES IN DIMENSIONAL FORM.

Fig. 7 Matrix equations showing effects of c.g. location.

Table 1 Performance Benefits of Hard SAS[a]

	Baseline Values	Improvements Net	Improvements Percent
Range increase (naut mile)	3,200	225	7.0%
Takeoff speed reduction (knot)	197	5	2.5%
Takeoff field length reduction (ft)	10,800	500	4.6%
Takeoff community noise reduction reduction (pndb)	105	1	0.95%
Landing approach community noise (pndb)	111	2	1.8%
Landing approach speed reduction (knot)	153	5	3.3%
Landing field length reduction (ft)	8,250	350	4.2%

[a] Analyses conducted in mid-1968 for a 750,000-lb MTW airplane carrying 48,906 lb of payload on a standard plus 8° C day.

The airplane was required to undergo a checkout test flight anytime more than one channel of HSAS was removed and replaced. This was required to prove that the airplane was safe for public use.

The use and meaning of reliability calculations were examined. It was concluded that reliability calculations are really only applicable to a system that has had the design errors worked out of it. Reliability calculations are useful for determining the better of several design approaches, but they cannot assure safety during the first few hundred hours of flight. Hence, when flight safety is to be dependent on control augmentation systems, the development program should be planned so that safety is not made dependent on new developments until the reliability of the new designs is tested in the true flight environment. This was achieved for the SST design by providing an all mechanical backup control mode. For early flight tests, the airframe would have been lightly loaded with a forward c.g. where it could be safely flown without HSAS. Piloted flight simulation tests showed the SST could be flown in all conditions on the mechanical only mode, but with an aft c.g. its handling qualities degraded to a questionable level (Cooper ratings aroung 7.5) for critical landing approach conditions.

Since the mechanical control path from the column to the surface actuators was for a backup control mode only, and was in no way essential for ECSS or HSAS control, a single load path design was used to minimize weight and complexity. The resulting layout of the SST pitch axis primary flight controls is shown in Fig. 6.

Basic Augmentation Requirements

Since the airplane was designed to fly with the c.g. behind the center of lift for aft c.g. loadings in subsonic flight, it is of interest to examine the effects of c.g. location on aircraft dynamics. Figure 7 shows the effects of c.g. shift separated out of the linearized, body axis aircraft equations of motion. From the matrix equation of Fig. 7, it can be observed that shifts in c.g. location affect all the moment derivatives, but the predominant effects are the changes to the derivative of pitching moment with respect to the angle of attack (M_α), and the derivative of pitching moment with respect to speed (M_u). For a rigid

†CPC's are electronic signal selection devices, such as voters with failure monitoring and failure isolation capability.

Table 2 Comparison table for sensor selection study

Considerations	Rate gyro	Accel	α sensor	Position gyro	Speed[a] sensor
Augmentation capability	good	good	excel	good	good
Sensor reliability	good	good	poor	med	med
Mechanization complexity	good	good	med	poor	med
Structural mode sensitivity	good	poor		good	good
Channel tracking capability	good	med	med	good	good

[a] From an air data computer.

airplane in subsonic flight, the effects of c.g. shift on M_u would be negligible, but for the SST, which was flexible, and where Mach effects were large, including the effects of c.g. shift on M_u could make as much as 2% of wing root chord (C_R) difference in the required forward shifting of the c.g. to achieve stability. The effects of c.g. shift on the derivative of pitching moment with respect to pitch rate (M_q) are normally small, but a minimum tail size airplane will require pitch rate feedback to achieve adequate damping. From these observations we conclude that ideally angle of attack, speed, and pitch rate feedback to a pitching moment control surface could be used to establish the desired stability characteristics to an airplane with the c.g. located behind the neutral point. A typical SST characteristic equation root loci for c.g. shifts is shown in Fig. 8. Figure 9 shows a root map for the pitch attitude response to stabilizer deflection (Θ/δ_H) for different flight conditions. Most subsonic, aft c.g. flight conditions for the SST had a single root in the Right Half Plane (RHP). The root loci in Fig. 8 shows that if the c.g. were moved forward, the unstable root becomes more stable, but the damping on the short period roots decreases rapidly. The SST augmentation design had to compensate for a combination of aft c.g. location effects, small tail size effects, and mach tuck or speed stability effects.

Feedback Requirements for Complete Stability

It is of interest to determine the capabilities of available feedback sensors to establish complete stability of the aircraft. The transfer functions for the response of a pitch rate gyro (Q) and a pitch accelerometer (A_z) to a stabilizer deflection (δ_H) have the form shown below.[2]

$$\frac{Q}{\delta_H}(s) = \frac{K\theta_H s(T\theta_1 s + 1)(T\theta_2 s + 1)}{(s^2/\omega_{sp}^2 + 2\xi sp/\omega_{sp}^2 s + 1)(s^2/\omega p^2 + 2\xi p/\omega p\, s + 1)}$$

and

$$\frac{Az}{\delta_H}(s) = \frac{-K_{AH} s(T_{A1}s + 1)(T_{A2}s + 1)(-T_{A3}s + 1)}{(s^2/\omega_{sp}^2 + 2\xi sp/\omega_{sp} s + 1)(s^2/\omega_p^2 + 2\xi p/\omega p s + 1)}$$

where ξ_{sp}, ω_{sp} = damping and natural frequency of short period roots, ξ_p, ω_p = damping and natural frequency of phugoid roots, $K(\,)$ = static gain. Since both of these transfer functions have a zero at the origin, neither feedback could provide complete stability to the unstable aircraft

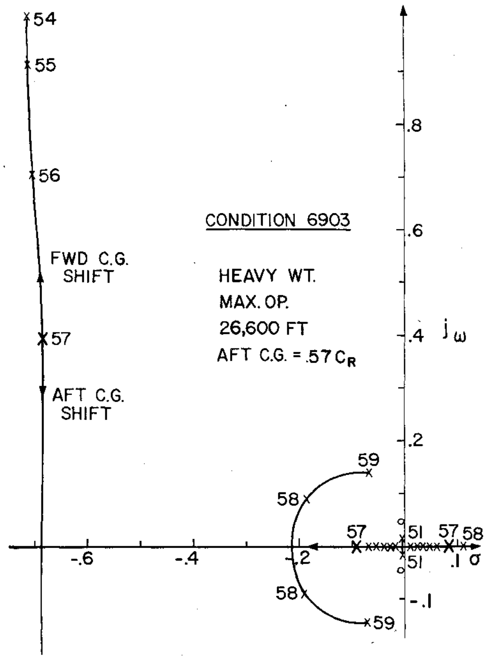

Fig. 8 Root loci as c.g. shifts.

without an integration‡ in the control loop. The zero at the origin will prevent the pole in the RHP from crossing into the left-half plane (LHP). Because of this, the HSAS criteria was written to allow a pole in the RHP providing the time to double amplitude was not less than six seconds and the pilot handling qualities rating criteria were complied with. Analytical studies that are beyond the scope of this paper, showed that either a speed feedback, or a pitch attitude feedback used in conjunction with either a pitch rate gyro normal accelerometer, or angle of attack sensor would be required to establish complete stability. Use of only angle of attack data would have been capable of establishing satisfactory stability in only part of the unstable flight regions.

Sensor Selection

Table 2 lists the considerations for sensor selection and shows a relative rating of the sensors that were considered. As a result of the sensor selection studies, rate gyros

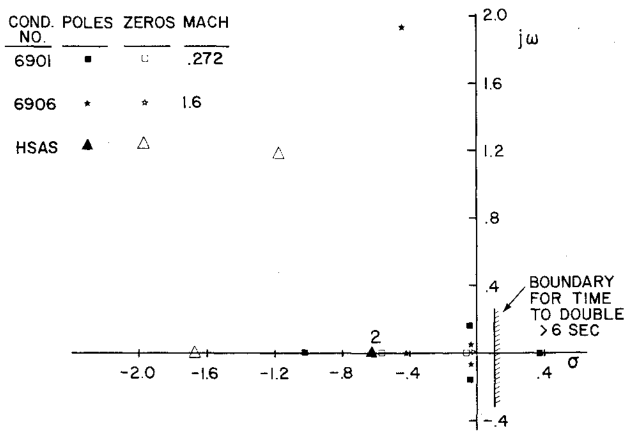

Fig. 9 Root map of Θ/δ_H and low frequency HSAS roots.

‡There are several reasons for avoiding an integration in the HSAS augmentation loops. One reason is the ground air transition problem. Another reason is that it would hide the basic aircraft trim characteristics, but it would require a sensor trim.

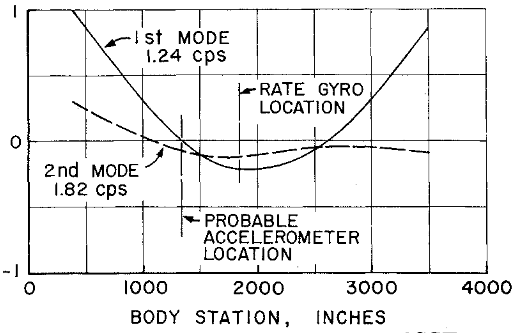

Fig. 10 First two bending modes of SST.

were selected for both the HSAS and the ECSS application because they were good in all respects. Accelerometers were found to be inferior to rate gyros in their sensitivity to structural mode uncertainties and/or sensor location errors. This can be observed from Fig. 10 which shows the first two mode shapes along the X-axis. The rate gyros should be located on the phase stabilizing side of antinodes whereas the accelerometers should be located on the phase stabilizing side of nodes. The curvature at the antinodes is usually smaller than the slope at the nodes for the low frequency modes.

Although angle-of-attack sensors have desirable augmentation characteristics they were considered unsatisfactory because of reliability and channel tracking considerations.

Speed feedback was selected as the additional feedback variable to provide complete maneuver stability in the ECSS for the following reasons.

1) The unstable mode was primarily a speed divergent mode and the speed feedback had the strongest effect in stabilizing this mode.

2) Mach and/or compressible dynamic pressure signals would be required for gain scheduling in the ECSS; hence use of these signals for the speed feedback would eliminate the need for additional sensors in the ECSS.

3) Speed feedback allowed the potential of providing near normal speed stability characteristics, whereas a pitch attitude feedback would have provided only neutral speed stability like an attitude hold mode.

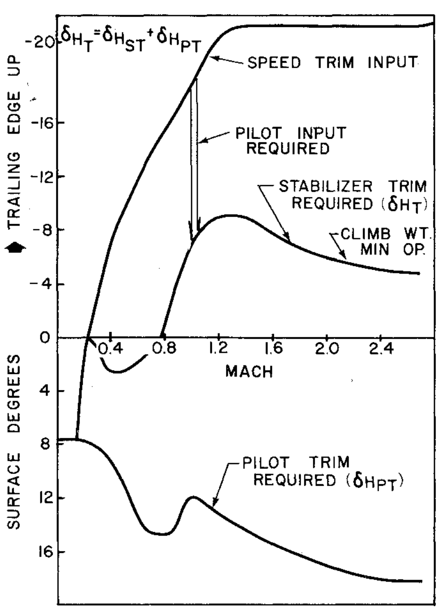

Fig. 11 Typical trim requirements and speed feedback trim.

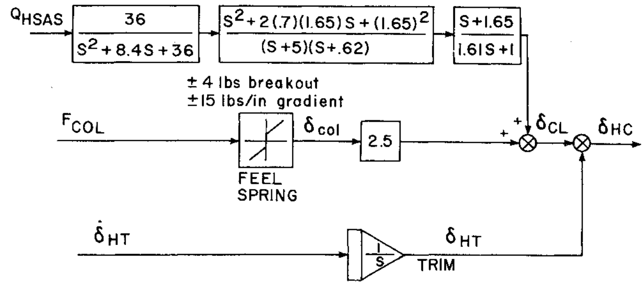

Fig. 12 Block diagram of HSAS control law.

Speed Stability Augmentation Requirements

The speed stability problem is an expanded version of the subsonic Mach tuck problem. Figure 11 shows an example of the basic aircraft trim characteristics and the speed feedback trim function for a nominal flight profile. These curves sum together to give the augmented aircraft a stable speed-trim characteristic everywhere except thru the transonic region where a maximum 15-lb reversal was allowed. This speed trim function served as the speed feedback signal. To assure the desired speed stability characteristics, it was necessary to make the speed trim schedule a function of both Mach and compressible dynamic pressure (q_c). This was accomplished by making the speed trim signal $\delta H_u = \delta H_q(q_c) + \delta(H_M)$ (Mach). The speed feedback gain K_u then was

$$K_u = \frac{\partial \delta H_M}{\partial\ \text{Mach}} \frac{\partial\ \text{Mach}}{\partial u} + \frac{\partial \delta H_q}{\partial q_c} \frac{\partial q_c}{\partial u}$$

An augmentation filter was required so that

$$\frac{\delta H}{\Delta u}(s) = K_u \frac{(2S + 1)}{(.2S + 1)}$$

A minor problem which was never thoroughly resolved was that when the speed feedback gain was made high enough to achieve the desired phugoid stability characteristics, then the stick force per knot trim requirements were so high they were slightly objectionable to the pilots.

Control Law Synthesis

It is beyond the scope of this paper to give a thorough discussion of the control law synthesis problem. The magnitude of the problem is partially demonstrated by the root map (Fig. 9) of the pitch attitude (Θ) response to stabilizer deflection (δ_H) for two different flight conditions. The roots are for the rigid body equations corrected for static elastic deformations.

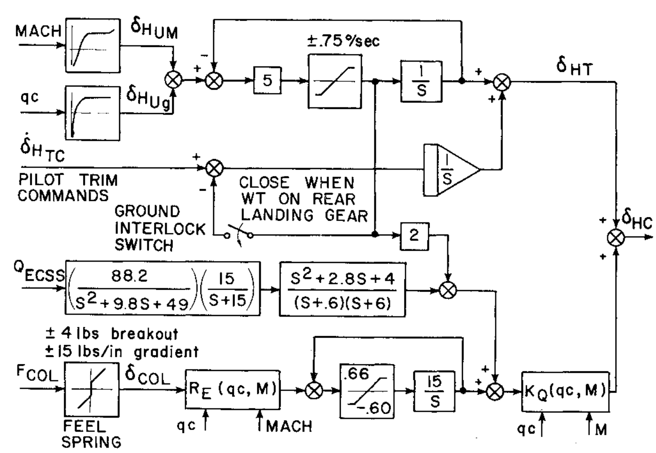

Fig. 13 Block diagram of ECSS control laws.

HSAS Control Laws

Figure 12 is a block diagram of the final§ HSAS control laws. The low frequency HSAS roots are also located on the root map of Fig. 9 which shows a pair of complex zeros in the HSAS filter located to attract the short period roots of the aircraft.

ECSS Control Laws

A block diagram of the final ECSS control laws is shown in Fig. 13.¶ The ECSS filter also has a pair of complex zeros similar to the HSAS. Of special interest is the ground air transition problems encountered with the speed stability mechanization. Common practice is to set the pitch trim before takeoff to the calculated trim requirement at $V_2 + 10$ knots. Since the speed feedback was required for minimum operating speed conditions which were less than the heavy weight liftoff speed, there was a problem with the speed feedback altering the trim setting during the runway roll. The solution was to use ground interlock switches operated off of the rear landing gear oleo struts to synchronize the speed trim function to the manual trim setting until the airplane is flying.

HSAS-ECSS Interface Design

It was desirable to have capability to modify any part of the ECSS control laws during the flight test program without the necessity to modify the HSAS. Also, there was doubt about the feasibility of designing an ECSS which could satisfactorily augment the HSAS with a single ECSS to HSAS interface, because early HSAS studies showed the need to attenuate the HSAS gain at the supersonic flight conditions in order to improve damping. Therefore the HSAS signal was negated for ECSS operation as shown in Fig. 14. The negation technique used, subtracted the HSAS signal from the ECSS signal to produce a difference signal that was then authority limited. This authority limited difference signal was then added to the HSAS signal to produce the final ECSS signal that was used for normal control.

The speed trim signal was interfaced into the HSAS by generating a total trim command in the ECSS and then slaving the HSAS trim integrator to the total trim command. This made the trim interface signal nominally zero, so the signal path could have been opened at any time without creating a transient.

Gust Stability

The unstable airplane can be augmented to behave in a normal manner to control inputs, but without use of an alpha sensor, it cannot be augmented to show the stable short period characteristic of pitching into a gust. This is not a deficiency since the gust response pitching of an airplane with strong positive stability is an undesirable characteristic that must be attenuated to provide acceptable turbulence penetration characteristics. Attitude hold autopilot modes are considered best for penetrating heavy turbulence and are currently employed in modern commercial jet transports. The augmented airplane can be made to behave similar to an attitude hold mode. Also, it was necessary to verify that after the aircraft had incurred two hydraulic system failures, the control surfaces still had sufficient rate capability to maintain aircraft stability in heavy turbulence.

§Final at date of program cancellation.

¶The block diagram illustrates the functional requirements, and does not represent the actual mechanization.

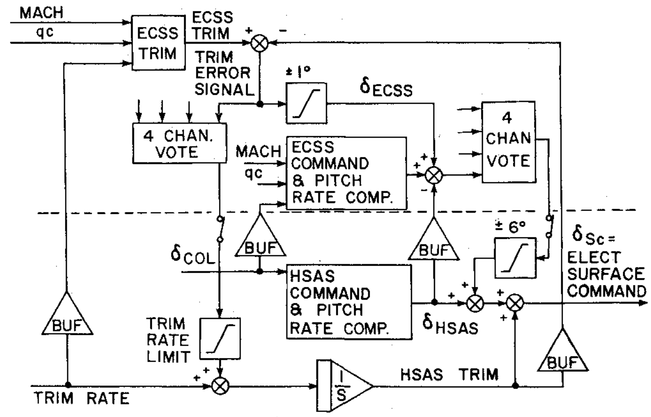

Fig. 14 HSAS-ECSS interface.

Structural Mode Constraints on Artificial Stability

As the basic aircraft becomes more unstable, a higher augmentation gain will be required to provide satisfactory handling qualities. The low frequency structural modes will always impose gain limitations beyond which a structural mode can no longer be gain stabilized. Even if it is elected to allow phase stabilization of the first one or two structural modes, it is always necessary to be gain stabilized at some higher mode. Thus the structural modes impose definite limitations on the amount of airframe stability that can be compensated for by an augmentation system. These limitations were a dominant consideration in the SST design.

Augmentation Authority Requirements

As the stability of the airframe decreases, the augmentation authority requirements, and hence the electric command (E.C.) servo authority requirements, increase. The nature of the augmentation authority requirements is illustrated by the surface time history responses to a step control column command shown in Fig. 15. For the neutrally stable case the surface moves to initiate the maneuver, and then comes back to near its trim position. For an unstable case, the stabilizer would have to hold a steady state value of opposite polarity to its initial displacement to hold a steady maneuver. If the unstable aircraft is to behave in a stable manner, then the E.C. servo must provide the difference between the control column position and the surface position required to perform the desired maneuver.

For normal operating conditions (no failures) the SST E.C. servo required an authority equal to about 60% of the total surface authority. Since this authority greatly exceeded the tolerable unaugmented surface transient over most of the flight envelope, the E.C. servo was given full surface authority in order to make the mechanical path nonessential. The mechanical path was made nonessential by generating the total surface position command in the electrical path and then subtracting the mechanical path signal from the electric path signal to generate the E.C. servo command (Fig. 16). There was no degradation in system performance for any failure in the mechanical path up to the summing point with the E.C. servo.

Requirement to Synchronize Mechanical Path

As the airframe stability decreases the sensitivity to failure transients increases and thus the tolerable transient, from which a pilot could recover the unaugmented airplane, becomes very small. If the mechanical reversion mode was to be useful, it was necessary to minimize con-

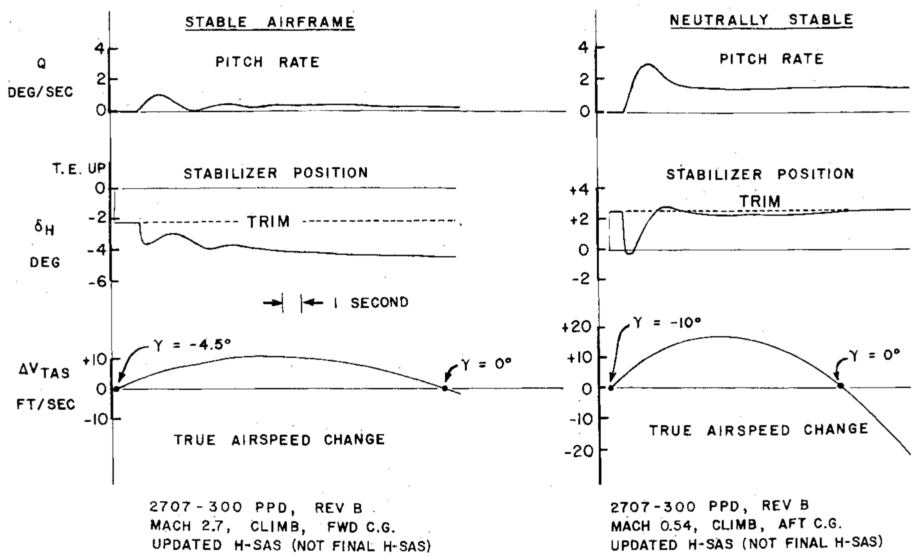

Fig. 15 Surface time history responses to 0.5g column step pullup.

trol transients that might occur when reverting to it. This was accomplished by a "Link Sync" control loop which synchronized the mechanical path to the surface position through use of the trim motors. Figure 16 shows a schematic of the "link-sync" mechanization which works as follows. The mechanical path is negated as was previously explained. The link-sync function is then accomplished by off-loading the E.C. servo position into the mechanical trim motor. i.e., the trim motors automatically run in a direction to offload the E.C. servos to a zero position. Since the mechanical reversion transient was equal to the signal being held by the E.C. servos, there could be no reversion transients if the servos were offloaded.

Increased Resolution Requirements

High resolution capability is a critical problem in redundant channel control systems which are required to vote out channel failures independent of the monitoring system. Consider, for example, the SST four channel control system which selected the output to be the mid value of the four channels plus a fifth zero vote. A determining zero vote is necessary in any system which can guarantee a passive last failure. Figure 17 illustrates how the output would have a deadzone about zero if the redundant channels have static offsets relative to each other.

While small deadzones are usually not critical in the control of stable aircraft, they are critical in the control of an unstable aircraft. This can be rationalized by observing that the deadzone leaves the unstable aircraft uncontrolled through the deadzone region. Deadzones will always cause limit cycle problems in the control loops which stabilize an unstable plant.

To avoid limit cycle problems in the SST control system it was necessary to devise a channel equalization scheme which would totally eliminate channel offsets at the voting E.C. servos. This equalization scheme is shown in Fig. 18. The basic concept was to use the trim integrators to equalize the E.C. servo offsets to zero. The electronic trim integrators are ideal for performing the equalization function because the trim commands are zero a major portion of the time thus leaving the integrators free to equalize the offsets to zero. Also, if the equalization loops were to cause the integrators to drift, then the drift can be trimmed out by the pilot.

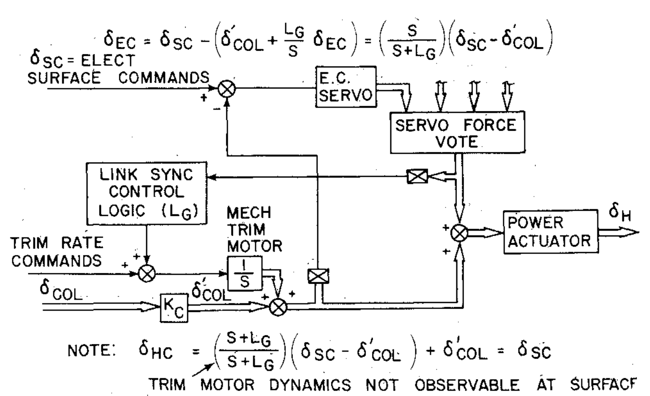

Fig. 16 Block diagram of "link sync" mechanization which synchronizes the mechanical path to the electric surface command.

Ground-Air Transition Problems

The ground-air transition problem encountered with the speed trim mechanization and the requirement for the ground interlock switch were mentioned previously. Two other ground-air transition problems of interest are discussed below.

Nose Wheel Loading Problem

Stable aircraft usually have the tail surface trimmed near to zero, or trimmed to produce a down load at takeoff. As the stable aircraft increases runway speed, the increasing aerodynamic tail loads act to relieve the nose wheel loads. The SST had a nose wheel loading problem that was caused by a combination of the takeoff trim setting requirements, and the speed trim feedback requirements. The problem is illustrated in Fig. 19. The trim setting range required at V_2 + 10 knots was in a negative (nose up) direction, but the speed trim feedback between lift off and V_2 + 10 knots required trimming the stabilizer to a position between +0.5° (nose down) to −1.3° before starting the takeoff. Thus the trim settings did little or

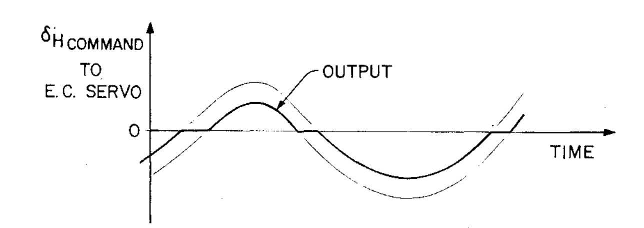

Fig. 17 Showing how a mid-value voting logic will cause a deadzone in the output if offsets exist between an even number of operating channels.

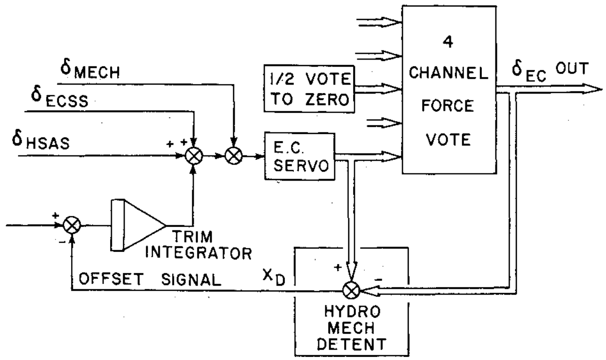

Fig. 18 Trim-integral equalization scheme.

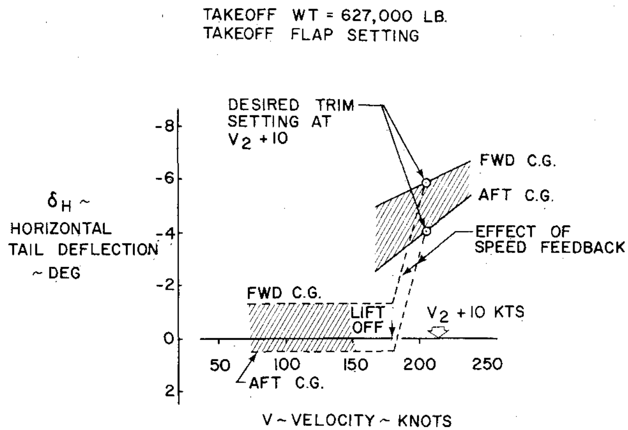

Fig. 19 Horizontal tail deflection required for takeoff.

nothing to relieve the nose wheel loads. This caused a requirement for critical attention to trim settings before takeoff, and a rule that the pilots must not push forward on the column during the takeoff roll, otherwise excessive nose wheel loads could occur.

Control Force to Rotate At Lift-Off

The trim characteristics which increase the nose wheel loading also increase the control force required to rotate the airplane for lift-off. When the trim is set in a more aircraft-nose-down direction to balance the aft cg in flight, the tail surface deflection required to rotate the aircraft for lift-off is increased. A greater tail surface deflection requires a greater control column deflection and thus a greater control force. Also, the pitch rate feedback subtracts from the column commands; thus, high pitch rate feedback gain also increases the control force required to rotate. When the airplane is balanced with the c.g. further aft, a higher feedback gain is required for stability.

The Boeing 747 has a desirable nominal 18-lb control force required to rotate. The Boeing 727 requires about 35 lb nominal to rotate. It was a design objective to keep the SST nominal force to rotate to 35 lb or less. It appeared the 35-lb limit could just barely be complied with. Up to 50 lb rotation force would have been required at the allowable mistrim limits for takeoff trim setting.

Conclusions

Substantial performance benefits can be derived from designing a control configured vehicle, but several unusual design problems arise. There are control system design solutions to all of these problems, but the design becomes complex, and program management problems greatly increase because of the greater interaction required between all the design disciplines. The configurations must understand the limitations of the control augmentation design. The augmentation system designers must worry more about the limitations imposed by structural modes. The trim system is likely to become an integral part of the augmentation system. Speed feedback may likely be required. New ground-air transition difficulties arise. Resolution and failure transient problems become more severe. At the termination of the SST program, solutions had been developed for all of these problems but the resulting control system was complex.

References

[1]Kehrer, W. T., "The Performance Benefits Derived for the Supersonic Transport Through a New Approach to Stability Augmentation," AIAA Paper 71-785, Seattle, Wash., 1971.

[2]Dynamics of the Airframe," BU AER Rept AE-61-4II, 1952, Bureau of Aeronautics, Washington, D.C. (Prepared by NORAIR Div. of Northrop Aircraft).