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final report

Avionics Requirements for All Weather Landing of Advanced SST's

Volume III
Specific Problems of an SST and Related Technological Trends

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SECTION VII

HANDLING QUALITIES AND SST ALL WEATHER LANDING

A. INTRODUCTION AND DISCUSSION OF CRITERIA

The subject of aircraft handling qualities tends to be controversial. This is partially caused by semantic difficulties experienced by various groups who represent different technical disciplines, but attempt to communicate with each other in an area that is inherently highly subjective. The intent of this section is to review the so-called "Handling Qualities" technology from the standpoint of its implications on all weather landing techniques for an SST.

An inquiry into SST handling quality factors should answer the following questions:

- Why is an SST more difficult to land than a Cessna 182, a Piper Cub, or even a T-33?
- Can the SST's landing characteristics be improved by avionics techniques?
- What are the implications of the SST's landing characteristics on automatic landing system performance?

A review of the literature on this subject shows that very little of the research that has been done addresses such questions directly. Most of the effort in this field is concerned with certain narrow aspects of stability and control. Quantitative criteria relating to stability and control have been established by various groups. These criteria have, in general, been determined from tests performed in simulators and variable stability aircraft. The most frequently used specification is MIL-F-8785, "Military Specification, Flying Qualities of Piloted Airplanes". It is also the most frequently misinterpreted and abused. This particular specification devotes only a few paragraphs to the aircraft's short period response dynamics; the subject that has received most of the attentions of the research community. The remainder of the specification is devoted to such handling quality criteria as control friction and breakout forces, control forces in accelerated flight, control forces in takeoff, etc.

The misinterpretation of handling quality dynamic specifications has been prevalent primarily in relation to the design of automatic stabilization equipment. Specifications such as MIL-F-8785 were written for vehicles without electronic augmentation. Even if one attempted to apply a literal interpretation of the dynamic criteria in MIL-F-8785, ambiguous results can be obtained for typical stability augmentation systems. Consider the well-known lateral stability criteria as an example. Lateral dynamic performance is evaluated in terms of cycles to half amplitude versus the rolling parameter ϕ/V_E (bank angle to side velocity ratio). In the unaugmented aircraft with a pronounced dutch roll oscillation, there is no question regarding the measurement of these parameters. However, in a well-damped aircraft, the ϕ/V_E ratio cannot readily be identified with a lateral oscillation. The value of ϕ/V_E during any transient will depend upon the nature of the disturbance. Thus, we identify a cycle to half amplitude or the related damping ratio, but we cannot associate it with a specific roll to side velocity ratio.

Two main abuses associated with the application of dynamic handling quality criteria can be noted. First, there is the general problem of attempting to apply them to aircraft - electronic stabilization system combinations. Then, there is a question regarding the validity of the criteria for large aircraft. The main difficulty in the first category seems to be the lack of appreciation of a difference between the command and disturbance response. When handling quality criteria specify aircraft natural frequency, low frequencies are considered objectionable, even when well damped. A relatively simple system to design is one that provides very sluggish and overdamped disturbance responses, but rapid and precise command responses. This type of system, often referred to as a Command Augmentation System, requires electronic signals derived from the pilot's stick as well as from the aircraft motion sensors. The use of Command Augmentation Systems for aircraft manual control has not been too prevalent. The application of the simpler Stability Augmentation System is considerably more widespread. However, the recent impending introduction of very large transport aircraft resulted in a new requirement for Stability Augmentation Systems. The very large aircraft have very low pitch natural frequencies. The handling quality specifications do not allow such low frequencies. A pitch stability augmentation requirement was therefore created to modify the aircraft's pitch natural frequency. This artificial stiffening is easily achieved by feeding back a function of pitch attitude or angle of attack as well as pitch rate. The fallacy is that increasing the pitch natural frequency in this manner cannot speed up the pitch command response. Indeed, a fundamental principle involved here states that negative feedback of aircraft motions can only slow up the command response. Ironically, the reason for the frequency criteria is that pilots prefer a relatively rapid command response.

The artificial stiffening of an aircraft's pitch response actually makes the aircraft less responsive to commands, but it will now meet the handling quality criteria. This can be demonstrated by referring to figures 7-1a and b. In figure 7-1a, the analogy to negative feedback around a first-order system is drawn. Here the feedback gain K around an integrator determines the time constant of the exponential response. As K is increased, the time constant is reduced from τ_1 to τ_2. Note, however, that for the same command input, the shorter time constant (stiffer system) is less responsive. This analogy is carried to the case of the pitch response in figure 7-1b. Here a fixed stick command produces the low frequency oscillatory response in the unaugmented aircraft. A

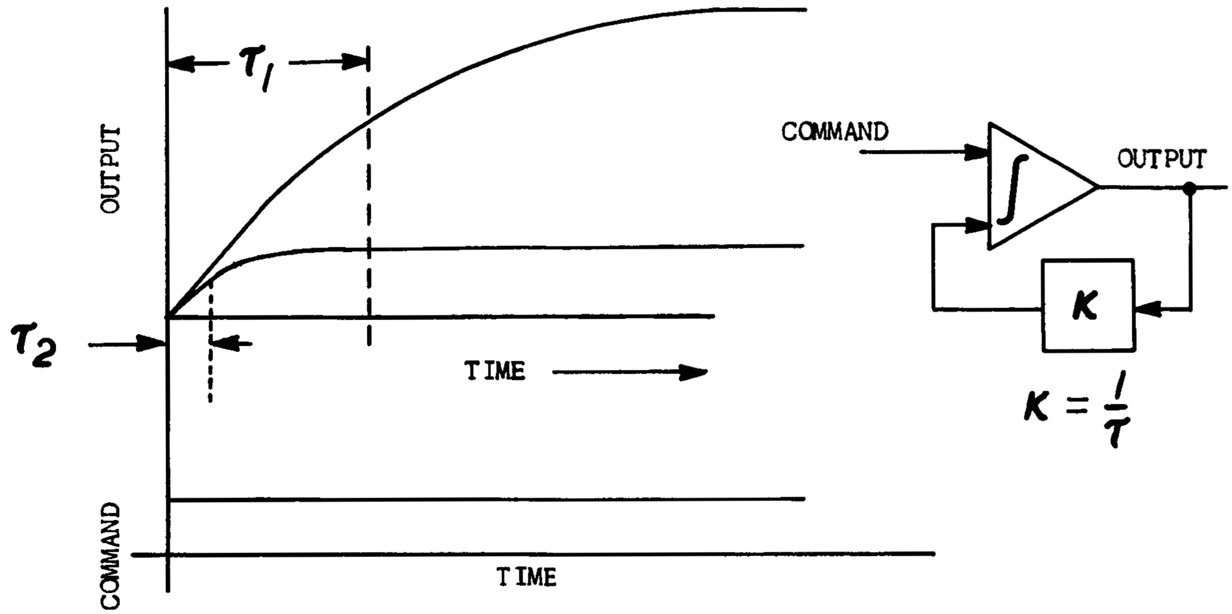


Figure 7-1a
Effect of Negative Feedback on Response

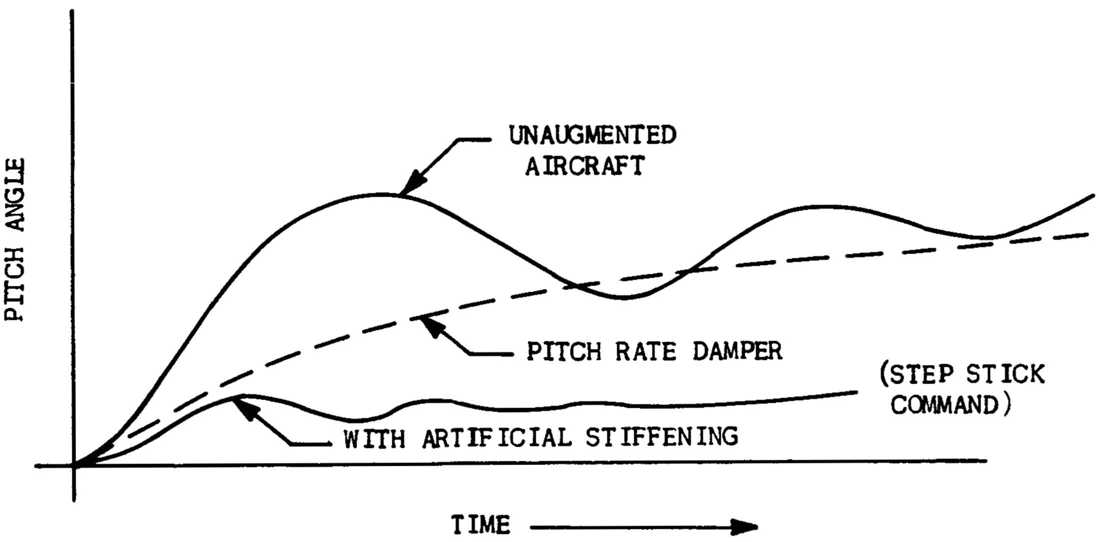


Figure 7-1b
Effect of Negative Feedback Artificial
Stiffening System on Pitch Response

pitch rate damper removes the oscillations, but the response is even more sluggish. The effect of artificial stiffening shows a much higher frequency; but for the same command the aircraft response is reduced considerably.

When artificial stiffening of this type is used in conjunction with variable stability aircraft, the command is altered to compensate for the effective command gain reduction. This requires access to stick command information and an electronic loop to properly weigh the amount of stick command information transmitted to the control surface actuators. In effect, the elements of a Command Augmentation System are used.

The second problem area regarding the validity of dynamic handling quality criteria stems from the methodology by which they were obtained, namely variable stability aircraft flight tests. Initially, the most widely used dynamic criteria were based on the Cornell Aeronautical Laboratory (CAL) variable stability aircraft flight tests. The longitudinal handling quality criterion is commonly referred to as the CAL "thumbprint". The lower frequency portion of this thumbprint is shown in figure 7-2 (as derived from reference 42). The thumbprint was a result of subjective pilot assessments based on a particular type of vehicle performing a particular mission at specific flight conditions. The assumption that these criteria could be applied to other aircraft flying different missions at different flight conditions is not necessarily valid. Note, for example, the various performance comments superimposed on regions of the thumbprint in figure 7-2. The comments regarding trim are most prevalent, but trim characteristics have almost no relationship to natural frequency and damping ratio, the coordinates of this plot. Where the linear second-order dynamics of the aircraft's pitch response are applicable, the trim characteristics are most influenced by the zero of the pitch to elevator transfer function. This zero is a function of the lift curve slope, the aircraft's linear momentum and the dynamic pressure. Variable stability aircraft cannot adequately duplicate this characteristic and it does not appear on the thumbprint; yet, it is ia most significant contributor to trim characteristics. At the low frequencies, the trim characteristics will be influenced by speed change effects, but these are also not included in the thumbprint. Thus, an attempt to interpret the SST handling quality characteristic (shown in the bad region of figure 7-2) in terms of these criteria can lead to erroneous conclusions. Nevertheless, the CAL thumbprint has found its way into a number of vehicle/autopilot specifications where the control tasks were unrelated and the aircraft dissimilar.

One effort, several years ago, attempted to set forth handling quality design objectives as they applied to a specific class of vehicles, namely Civil Transport Aircraft (reference 43). The SAE document was an attempt to recognize that civil transport aircraft are bigger and heavier than fighter aircraft, and therefore pilots would expect them to fly differently. Figure 7-3, for example,

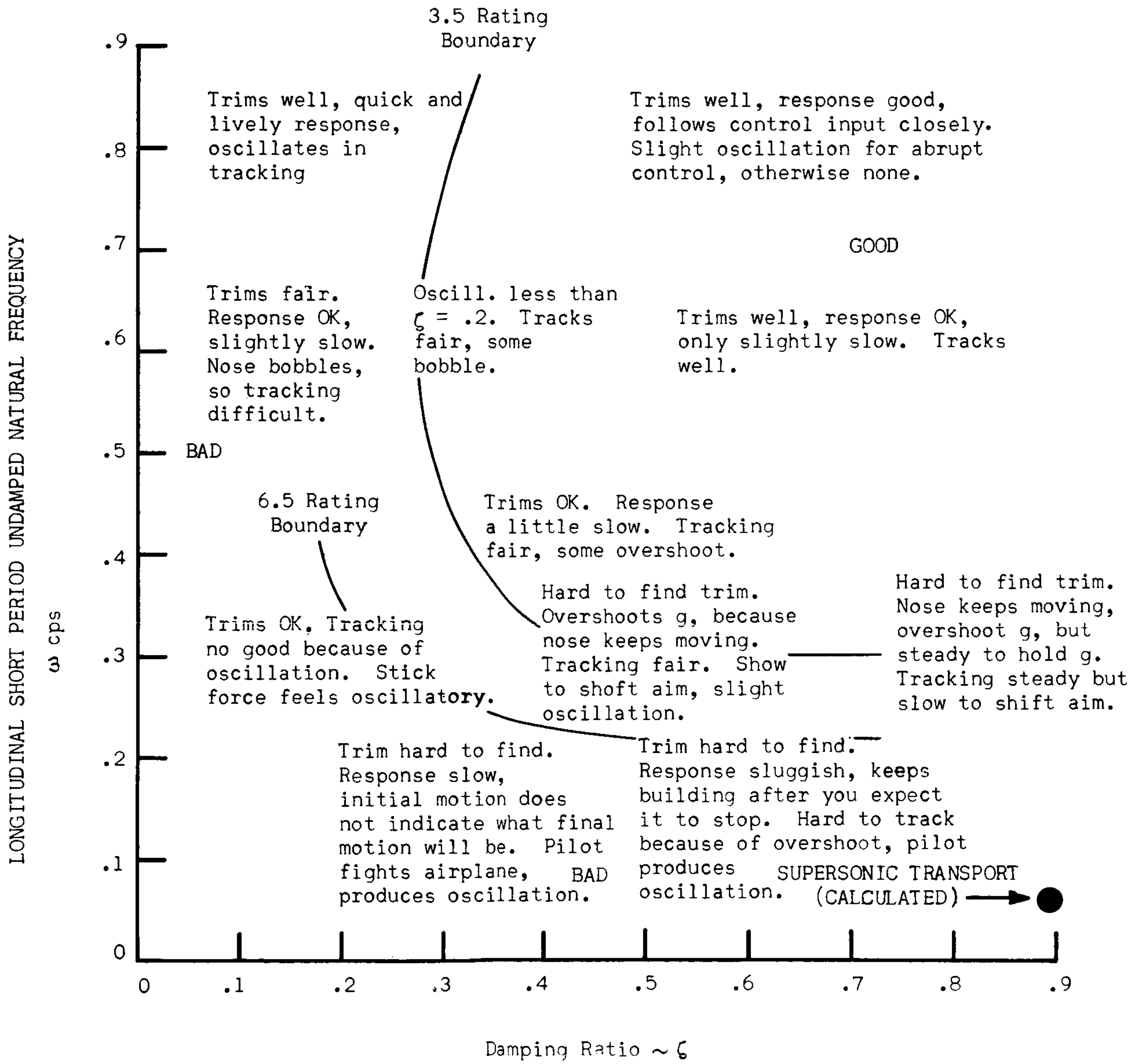


Figure 7-2
Pilot Rating of Longitudinal Short Period
Handling Qualities

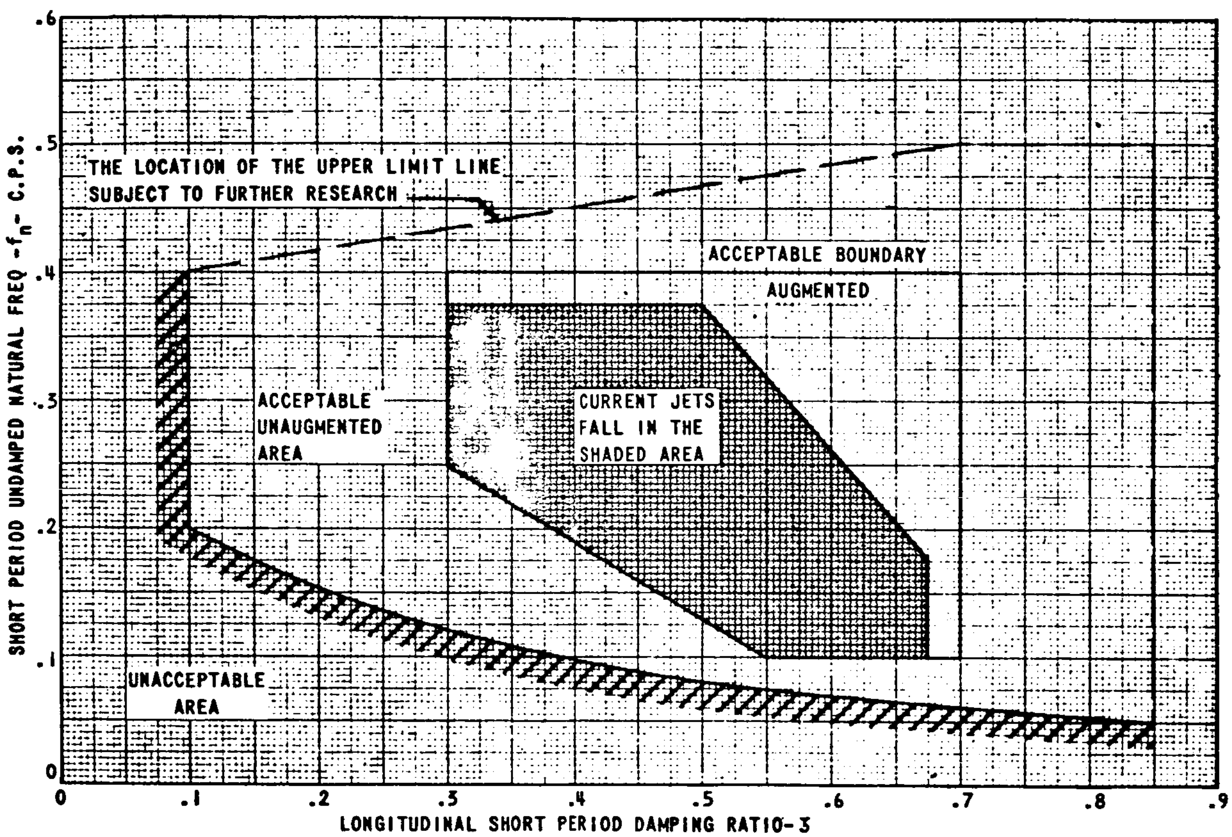


Figure 7-3
SAE Recommended Longitudinal Short Period
Characteristics for Transport Aircraft

shows the longitudinal thumbprint as recommended in the SAE document. Notice the much broader acceptable area for the transport aircraft. Also illustrated is the fact that most current transport jets do not fall into the "good" boundary shown in figure 7-2.

Another example of attempts to improve the definition of handling quality criteria is reference 44. It suggests the use of time history envelopes for longitudinal stability and control handling quality criterion based on vehicle acceleration and pitch rate. The use of time envelopes permits convenient assessment of meeting specification requirements by avoiding extensive interpretation of results from simulation or flight test recordings. Assumptions of second-order linear systems are not required. Figure 7-4, taken from reference 44, shows the recommended time history envelopes for the tracking and landing/approach flight conditions. The ordinate parameter, C^*/F_p, is an attempt to take into account pilot cues at various flight conditions. Specifically, the fact that the pilot uses normal acceleration cues at cruise conditions, and pitch attitude cues during approach and landing conditions, is reflected in C^*/F_p. C^* contains normal acceleration, pitch rate, and velocity information while F_p is merely the pilot input. For a derivation of C^*/F_p, refer to reference 44.

It is apparent from this brief view of the aircraft handling quality criteria that the questions posed at the start of this discussion regarding the SST's landing characteristics are not answered directly by the criteria established in variable stability aircraft tests. Such tests have not, in general, been applied to the landing task because the adequacy of the variable stability simulation is doubtful. In addition to aircraft dynamic characteristics, such factors as aircraft speed, pilot's position and runway view, control system response, and trim characteristics are important considerations.

B. SST LONGITUDINAL HANDLING QUALITIES

1. Pitch Response

A trend in transport aircraft design having a major effect on longitudinal handling qualities is the decreasing aspect ratio. This results in an increase in both pitch and yaw inertia with respect to the roll inertia. The SST design will continue this trend having even larger pitch and yaw to roll inertia ratios (references 45 and 46). In addition, the pitch inertia will be larger because of vehicle size. As a result, vehicle responses to pitch commands on the SST will tend to be more sluggish and insensitive. In the literature, this is usually followed by a statement saying the SST short period response must be speeded up over the entire flight envelope. The justification for such a statement is questionable. For example, variable stability aircraft tests in recent years have been used to evaluate low frequency (short period) vehicle characteristics (reference 42). Over 100 pilots flew the test vehicle achieving

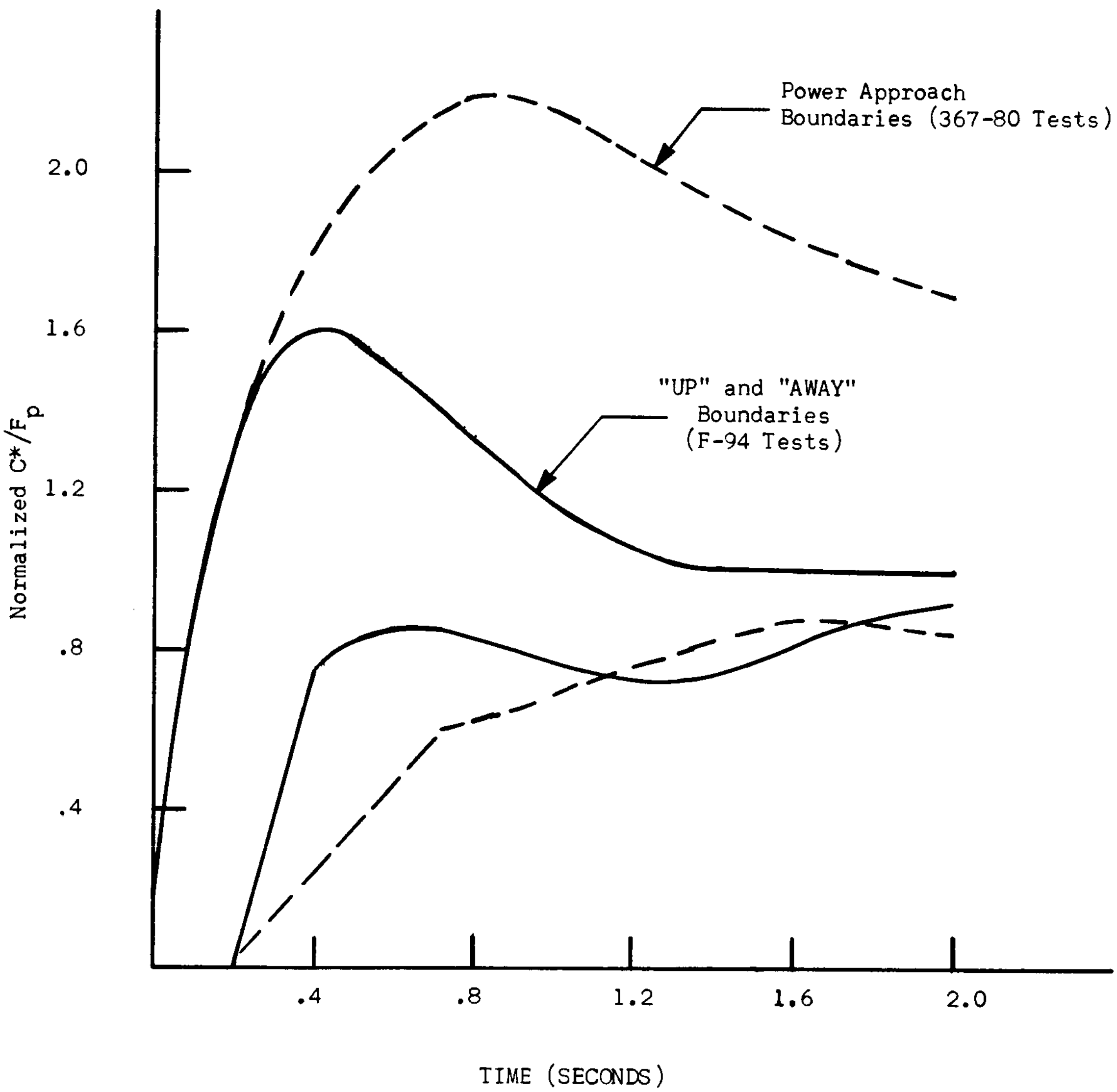


Figure 7-4
Recommended Time History Envelopes for Acceptable Longitudinal Handling Qualities

good performance when they accepted the fact that they were flying a slow responding vehicle. When the pilots attempted to get the response, there was a tendency to induce PIO (pilot induced oscillations). This is only natural. A pilot flying a 707 expects it to respond more slowly than an F-104. Airline pilots are conditioned to flying comparatively slow responding aircraft. The increased size of the SST should continue this trend of accepting slower responses for a variety of flight conditions. A possible exception occurs in the landing phase of flight which will be discussed later. However, it is noted that a sluggish response capability can be overcome with a Command Augmentation System. The elements of such a system are being included in all SST flight control system designs.

2. Short Period Damping

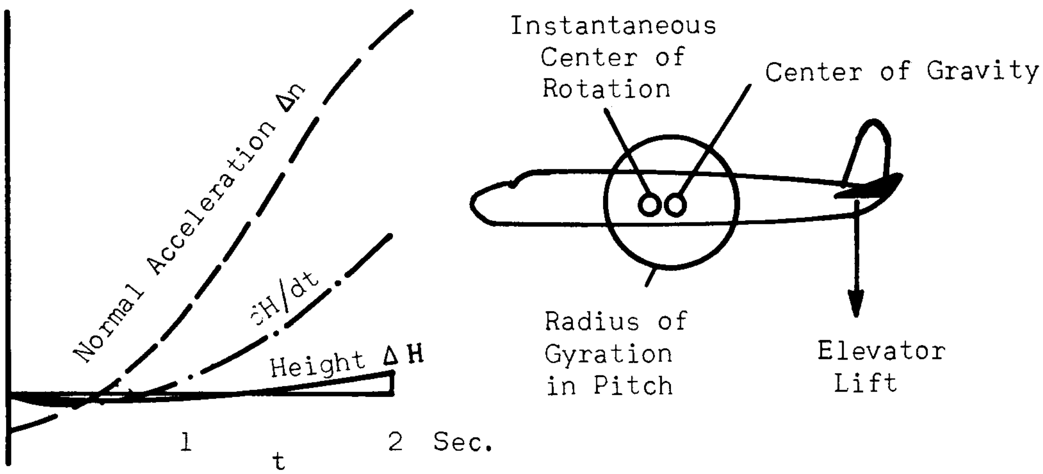
Another dynamic handling quality affecting pilot opinion is the longitudinal short period damping. At high altitude, high Mach, cruise flight conditions, the SST is expected to have damping ratios of 0.2 or less. Such low damping ratios result in poor handling quality ratings and should be increased. This, of course, is easily accomplished through the use of conventional Stability Augmentation Systems.

3. Approach and Landing

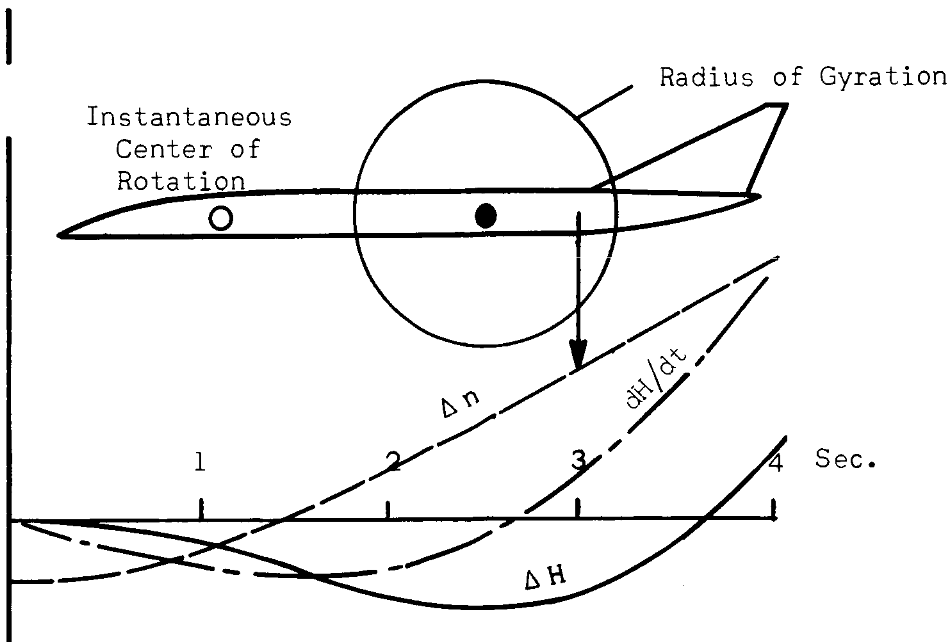
While a preponderance of data exists on the dynamic handling qualities for cruise condition, the opposite is true for the landing flight condition. The task of obtaining handling quality data for the landing phase of the flight presents a difficult problem because of simulation facility limitations. To evaluate the landing phase properly, the pilot should be exposed to the entire landing environment. Newer and more elaborate simulators are being developed to reproduce more of this environment in a realistic manner.

The slower SST longitudinal response will affect the landing handling qualities more than in any other phase of flight. First, the reduced response capability will increase the time required to change the vehicle flight path. As a result, flare initiation on the final approach must be at a higher altitude. Calculations in reference 42 indicate the SST flare initiation point could be at an altitude twice as great as the 707 flare initiation point. Higher flare altitudes increase the range of touchdown dispersions along the runway.

Another aircraft characteristic affecting landing handling qualities is the vehicle lift due to control surface (C_{L_δ}). The lift due to control surface deflection is a significant parameter during the landing phase of flight. Figure 7-5 (taken from reference 45), which shows longitudinal responses to step elevator commands, indicates the effect of large C_{L_δ} combined with increase pitch inertias for two types of vehicles. For both aircraft, the responses show



Low Speed Aircraft



British SST

Figure 7-5
Longitudinal Response for Conventional Aircraft and SST Showing the Effect of Elevator Moment Arm and Aircraft Inertia at Approach

an initial reversal in normal acceleration due to C_{L_δ} followed by a lagged response in accordance with the $C_{L_\alpha}/(mV/QA)$ flight path time constant. However, because of the larger control surface (relative to other lifting surfaces) on the SST, the initial loss in lift is significant enough to result in an initial loss in altitude at the vehicle cg. Normal acceleration responses for the Boeing Model 733 SST, from simulation studies at Sperry, are shown in figure 7-6. The landing approach flight condition (FC7) has a very sluggish g response with a significant g reversal due to C_{L_δ}. The resulting loss in altitude has a pronounced effect on the precision of final approach flight path control.

Note that although the vehicle cg initial response is in the wrong direction, the instantaneous center of rotation is quite forward of the cg. The pilot is a good distance forward of the instantaneous center of rotation (figure 7-5). Figure 7-7, from reference 45, shows the pilot to be 35.05 meters (115 feet) forward of the landing gear and 12.19 meters (40 feet) above the ground at touchdown for the SST. [Note that in the latest Boeing 2707 SST configuration the pilot is about 54.86 meters (180 feet) forward of the landing gear.] This puts him considerably forward of the instantaneous center of rotation. As a result, even though the vehicle cg is losing altitude, the pilot will experience what appears to be the proper response at flare initiation. In addition to vehicle responses affecting handling qualities, the pilot location in the cockpit will also influence his assessment of vehicle handling qualities. The location certainly has an effect on manual landing touchdown conditions. Data on touchdown conditions, from reference 45, are plotted in figure 7-8. It should be emphasized that the figure 7-8 presentation is a result of many other factors besides pilot location alone. The various handling quality effects discussed above all come into play. Also, such factors as increased touchdown velocities for the larger jets are important. Nevertheless, the trend toward increased distances between the pilot and aircraft wheels certainly has contributed significantly to the data presented.

4. Direct Lift Control

Use of Direct Lift Control (DLC) for improvement of vehicle handling qualities is a method often suggested to achieve improved aircraft performance, especially during the landing phase. While lifting surfaces having significant lift capability for flight path steering may not be feasible in an SST, the possibility of auxiliary lift devices for cancelling the adverse C_{L_δ} effect are promising. Results of studies and flight tests using DLC for Navy vehicle carrier landings are reported in references 47 and 48. DLC is currently under study by the Air Force to investigate possible handling quality improvements for path modes in other phases of flight.

Reference 47 reports on a flight simulator study directed toward determining the improvement in flight path control precision through the use of DLC

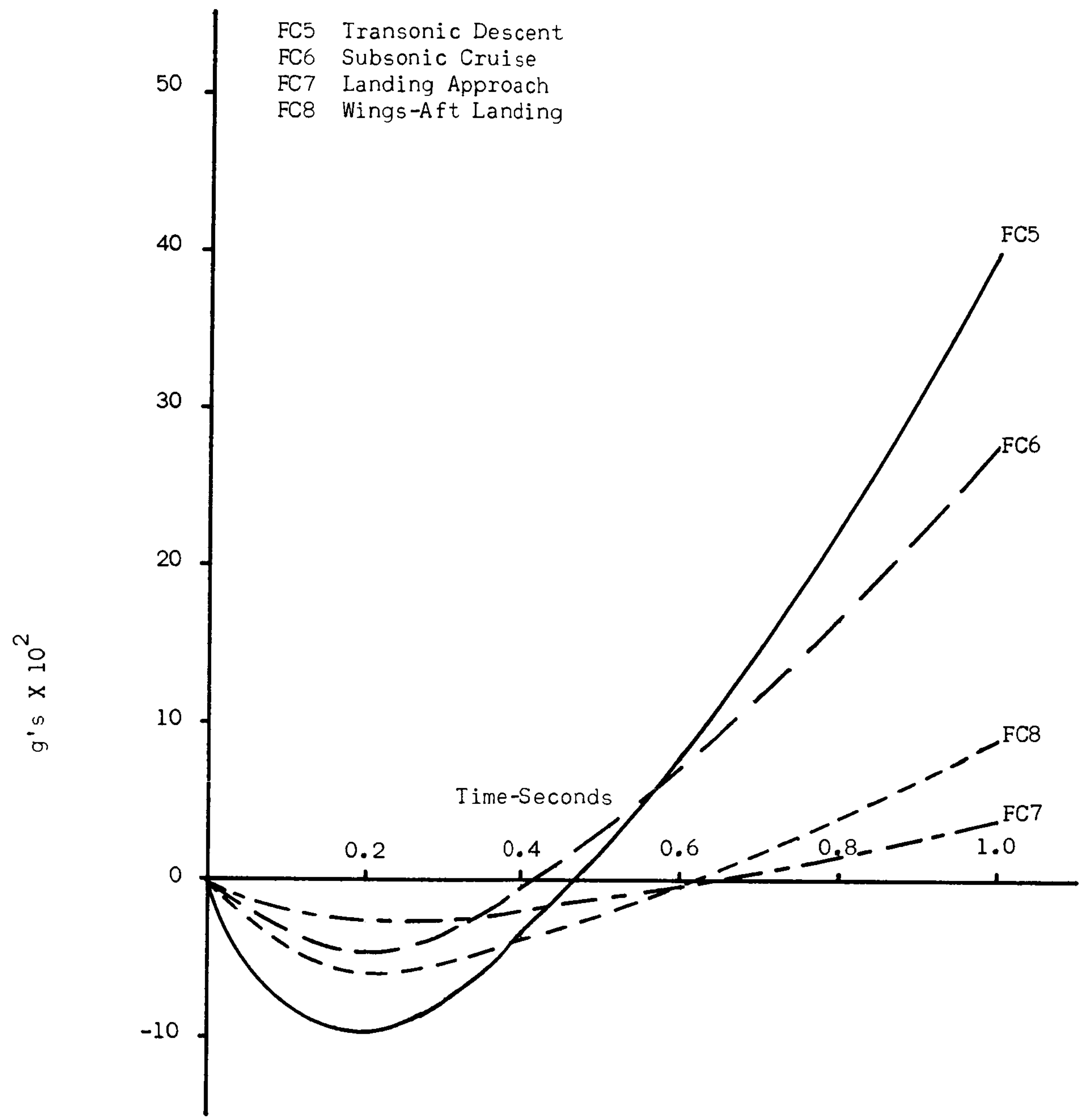


Figure 7-6
Relative g Build-Up Due to Step Commands of
4 Degrees δ at Various Flight Conditions

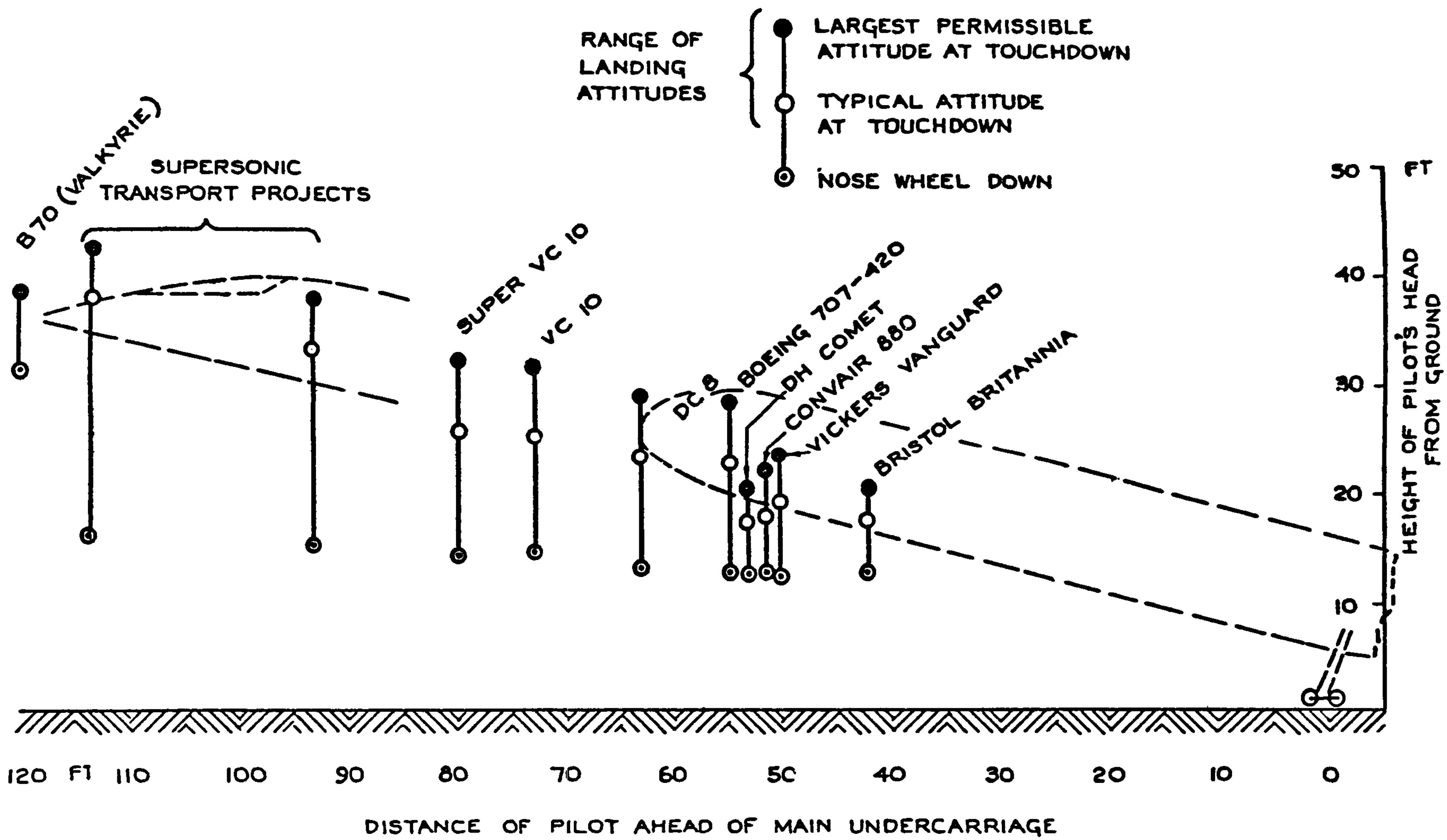


Figure 7-7
Pilot's Position with Respect to Main Wheels at Touchdown

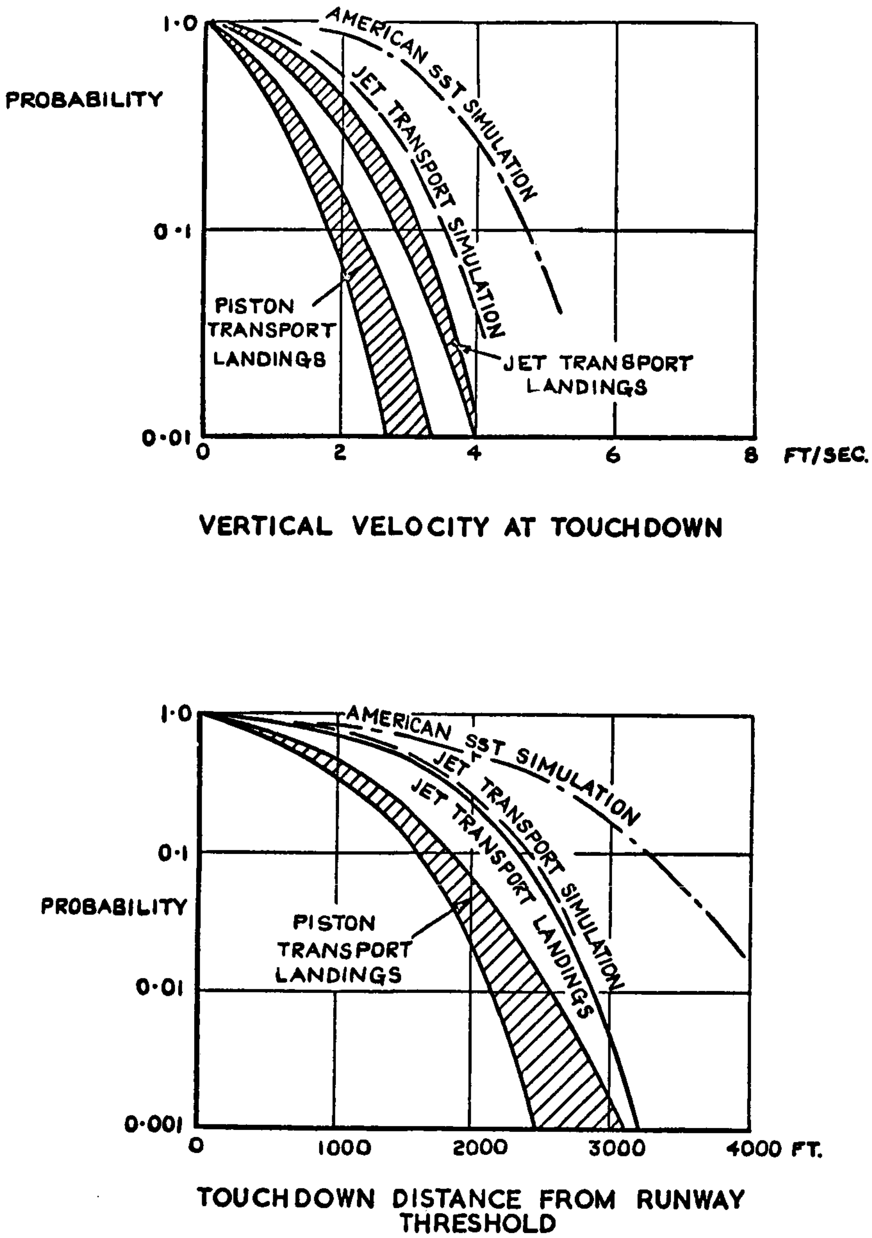


Figure 7-8
Variability of Touchdown Conditions
in Commercial Operations and
in Simulated Landings

flown manually. The simulated airplane was a twin jet, swept wing configuration, with a weight of approximately 50,000 pounds and a wing loading of about 60 pounds per 3.28 square meters (square foot). The pilot had independent control of lift via thumb wheel switches on the control stick. Twenty carrier-qualified pilots were enlisted in the simulation study to assess the effects of DLC on flight path precision and landing handling qualities. A conclusion of reference 47 states that "direct lift control is a most effective means of achieving better and more precise landing approach flight control and that widespread use of direct lift control appears to be imminent". However, the quantitative results showed the improvement to be quite small, reducing the rms altitude error by approximately 15 percent. At zero distance from touchdown, reference 47 showed an rms altitude error reduction from approximately 2.13 meters (7 feet) to 1.52 meters (5 feet) using DLC. In the important area of the not always predictable pilot assessment (handling qualities), reference 47 states that "pilot opinion was strongly favorable to direct lift control in all cases, even those with relatively good characteristics and only nominal altitude-error reductions".

Reference 48 reports on flight test results using DLC on the F-8 Crusader Navy fighter airplane. The study reported in reference 47 assumed perfect DLC; that is, lift control actuation produced lift but no pitching moment. Unfortunately, in a flying vehicle, this cannot be achieved. Even if an ideal location could be chosen, changes in cg caused by weight shifts and changes in aerodynamic center as a result of wing sweep will produce pitching moments at some conditions of flight. As a result, even though the F-8 Crusader is more readily adaptable to DLC than most other airplanes, a good deal of effort on the program was devoted to obtaining the proper pitching moment cancellation at the approach flight condition. In fact, an acceptable means of compensation was arrived at only after actual flight tests in spite of extensive simulation studies and wind tunnel tests. Reference 48 concludes that "direct lift control significantly increases the pilot's ability to control glidepath, and thus reduce touchdown dispersion". The quantitative statistical data based on a simulated approach showed the accuracy improvement to be rather insignificant. For example, the standard horizontal deviation at touchdown with autothrottle on was reported to be 5.12 meters (16.8 feet) using normal longitudinal control. Use of proportional DLC reduced this to 2.68 meters (8.8 feet). This cannot be considered a significant improvement in accuracy, in view of the fact that use of autothrottle alone reduced the deviation from 23.47 meters (77 feet) to 5.12 meters (16.8 feet). Therefore, use of DLC resulted in a vernier improvement on the dispersion reduction due to use of autothrottle. Nevertheless, in terms of pilot assessment (handling qualities), reference 48 reports that "after only a few flights, a given pilot understood the function of direct lift control and accepted it as a superior method of controlling the vertical parameters of flight path. After 8 or 10 flights, a pilot was generally quite proficient in the use of DLC and became an enthusiastic supporter of the concept".

To summarize then, the application of DLC to the manual landing problem appears to be assessed quite favorably by pilots flying both simulators and vehicles. However, test data obtained does not bear out the claim of significant improvement in flight path accuracy. Based on test results to date, one must conclude that DLC may have application to the SST, primarily for cancelling C_{L_δ} effects. Because of the complex relationship between DLC and vehicle configuration, combined with simulator limitations, any simulator result obtained must be carefully interpreted.

Practical consideration for DLC dictate that very significant improvements in landing technique and landing handling qualities must be demonstrated in the simulator before vehicle application. For example, the DLC is in fact an additional longitudinal control system. Therefore, all the reliability requirements of a flight safety item must be imposed on the system. DLC actuator performance must be comparable to the normal control system actuators. The problem of pitching moment compensation is a very difficult one. On flight tests, pilots reacted favorably only after a training period on the new control task required. While test pilots and military fighter pilots may accept such a new task, the commercial airline pilot is already saturated with complex workloads during landing and may not receive DLC favorably if it demands new control tasks.

5. Pilot Location

Perhaps the most important characteristic that makes an SST different from the present day jets relates to the cockpit location with respect to the aircraft landing gear. (Figure 7-7 shows the pilot's position in various aircraft.) This forward location also exposes the pilot to larger accelerations and motions due to fuselage flexibility. Some consideration is being given to body bending stability augmenters, but the feasibility of such a technique for the SST has not yet been established. However, the problem that looms as a major handling quality consideration is the poor view of the landing gear relationship to the runway during landing. This is borne out by B-70 experience. That aircraft located the pilot considerably closer to the landing gear than will the B2707. Nevertheless, it was identified as the most significant problem encountered in landing the B-70. A quotation from an interview with Colonel Joseph Cotton and other B-70 pilots in reference 49 illustrates this point. Colonel Cotton was asked if the landing phase is the critical part of flying a plane this size. His reply was:

> "I'll answer the question this way. If someone said to me, 'Tonight you're going to take a group of people in an XB-70 and you're going to Washington. What would you be concerned about?' my answer is simple - the landing in Washington. The takeoff? Your mother can do that if you happen to be busy. It's just so enjoyable and comfortable as long as the engines keep going. En route and all?

No problem. But I would be concerned about the landing. I'll be frank. That's what I was concerned about when I analyzed the whole thing. This airplane has beautiful landing characteristics, but it's where I'm sitting that concerns me. I'm 110 feet in front of the gear and 40 feet in the air, and I'm trying to find out exactly when it's going to touch the concrete. There's a certain amount of good old experienced technical guessing that goes on as to exactly when the wheels are going to touch the concrete. And I don't want to guess until I've got good firm concrete and everything under me. You don't want to put it within the first 1000 feet. If I ever do, it won't really be because I got used to it, it will be unintentional. I feel my landing spot is about 2500 feet down the runway."

C. SST LATERAL HANDLING QUALITIES

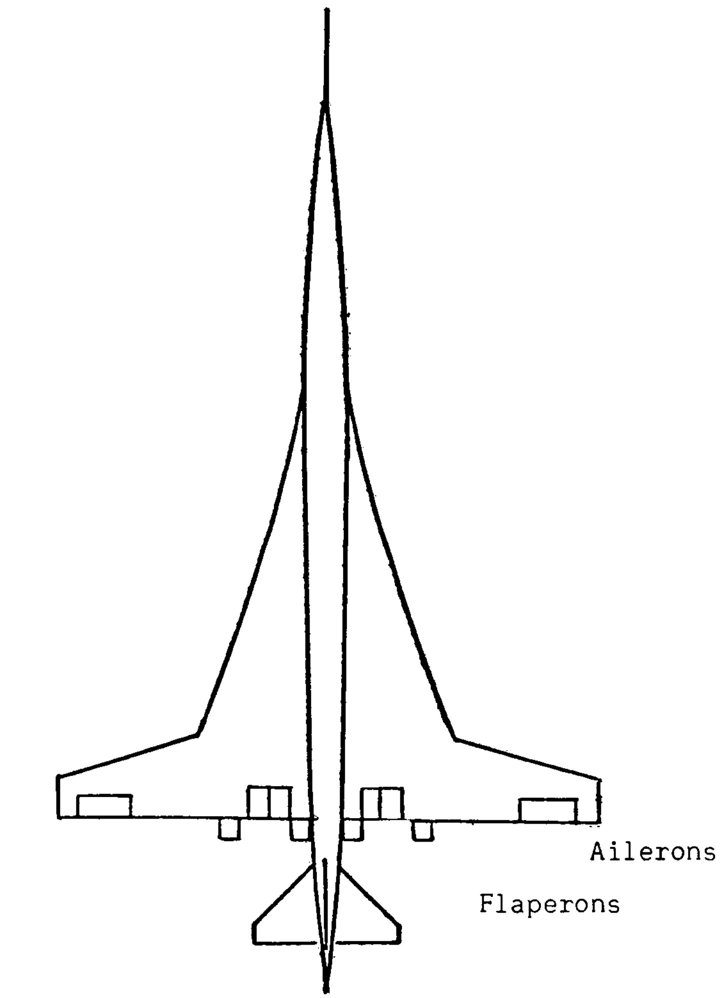
1. Introduction

There are many factors that affect lateral handling qualities, all intimately related because of significant lateral axis coupling. Most material written on the subject discusses only the stability type handling qualities such as a dutch roll damping, roll time constant, etc. One important handling quality consideration, not of the stability type, concerns the vehicle roll moment producing devices, their location, and their effect on responses to crosswinds and turning commands. Some comment on these factors are warranted before discussing aircraft stability characteristics.

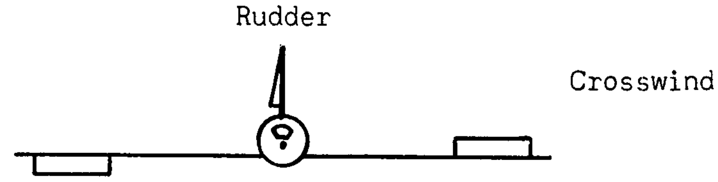
2. Control Surface Location

Consider the vehicle response to a crosswind at final approach. The normal pilot response to a significant crosswind condition, during approach for the SST vehicle, will be a bank into the wind combined with a rudder input for runway alignment. For a crosswind coming from the left, the pilot response is to roll left, and deflect the rudder to yaw right. For the variable sweep wing, shown extended in figure 7-9, the roll control surfaces are located in an extreme outboard position, thus providing good roll capability because of the moment arm. Note also, however, that ailerons in the depicted outboard condition produce "adverse yaw" (although not really adverse here). As a result, left roll control surface deflection will yaw the vehicle to the right, thus reducing the pilot input rudder requirement. When making a turn, the opposite is true for this configuration. A right turn would produce what is truly "adverse yaw" resulting in turn miscoordination, and thus requiring more rudder control from the pilot.

Consider now the vehicle design shown in figure 7-10. Inboard roll control surface location, similar to the double delta or retracted variable sweep configuration, produces sidewash effects on the vertical tail. The moments

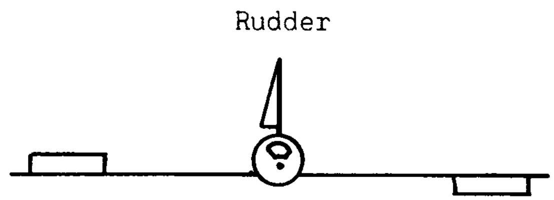


B733 SST ROLL CONTROL SURFACE LOCATION
- APPROACH CONDITION



Crosswind Approach

Adverse Yaw Reduces Rudder Requirements



Right Turn

Adverse Yaw Increases Rudder Requirements

Figure 7-9
Effect of Roll Control Surface Location
on Extended Wing SST, Lateral Handling
Qualities for Turns and in Crosswinds

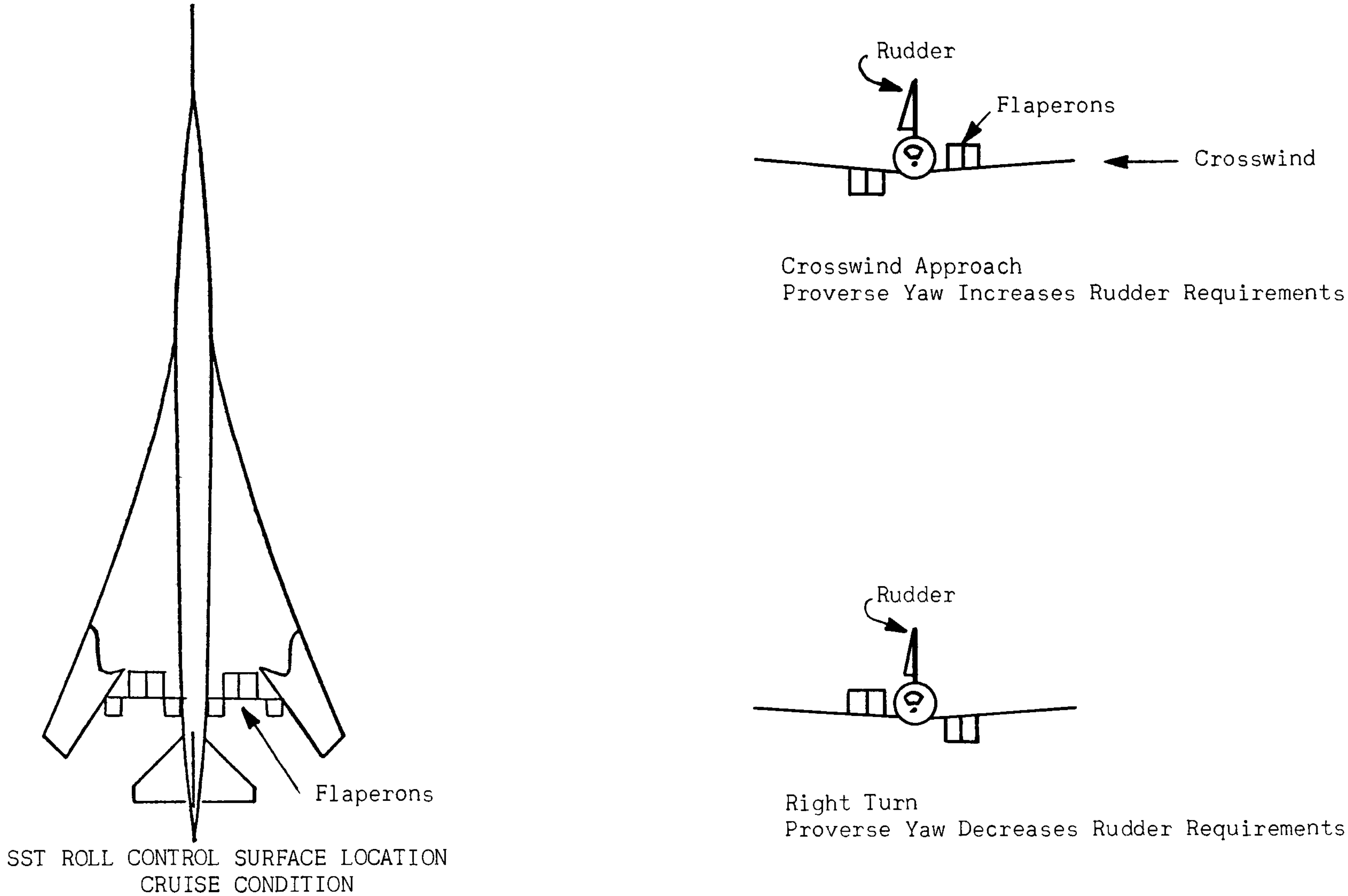


Figure 7-10
Effect of Roll Control Surface Location on Delta (Folded) Wing SST, Lateral Handling Qualities for Turns and in Crosswinds

produced by sidewash result in "proverse yaw". For example, when the same crosswind hits the vehicle depicted in figure 7-10, the proverse yaw effect tends to produce additional rudder requirements by the pilot. However, when entering a turn, the proverse yaw effect reduces the rudder requirements for a coordinated turn (figure 7-10).

With respect to the above discussion, the variable sweep wing SST design will have varying handling qualities as a function of flight condition. In high-speed flight, wings aft, roll control is through the inboard roll control surfaces (flaperons) with other roll control surfaces locked out. In low speed flight, with wings forward, the outboard surfaces are activated. As a result, the sweep wing SST will exhibit adverse yaw at flight conditions such as takeoff, transonic climb, subsonic cruise, and landing approach. Proverse yaw will be exhibited at flight conditions such as end of acceleration, transonic climb, and cruise. For landing, the result is favorable since responses to crosswinds are more important than turn coordination considerations.

3. Lateral Stability Type Handling Quality Considerations

In terms of stability type handling qualities, even a cursory review of the literature will produce an overwhelming number of suggestions for required vehicle handling qualities, many for the SST in particular. Refer, for example, to references 42, 46, 50, and 51, which in turn reference many others. A specific example of why one must be cautious in applying these criteria will be considered.

The roll axis stability parameters referred to in the literature as ω_ϕ/ω_D and T_R illustrate the point. Here ω_ϕ is the numerator second-order characteristic frequency and ω_D is the denominator second-order characteristic in the ϕ/δ_a transfer function. T_R is the roll subsidence time constant that appears as a pole in the lateral transfer function. This is commonly referred to as the roll axis numerator to dutch roll frequency ratio. The preferred ratio as a function of $|\phi/\beta|$, the roll to sideslip ratio, is shown in figure 7-11, taken from reference 50. Reference 50 also states that "with T_R optimum, ω_ϕ and ω_D somewhat less than $1/T_R$, and with δ_ϕ and δ_D small and nearly equal", a good airplane will have the following:

$$\omega_\phi/\omega_D = 1 \text{ for } |\phi/\beta| \text{ small}$$

$$0.75 < \omega_\phi/\omega_D > 1.0 \text{ for } |\phi/\beta| \text{ large}$$

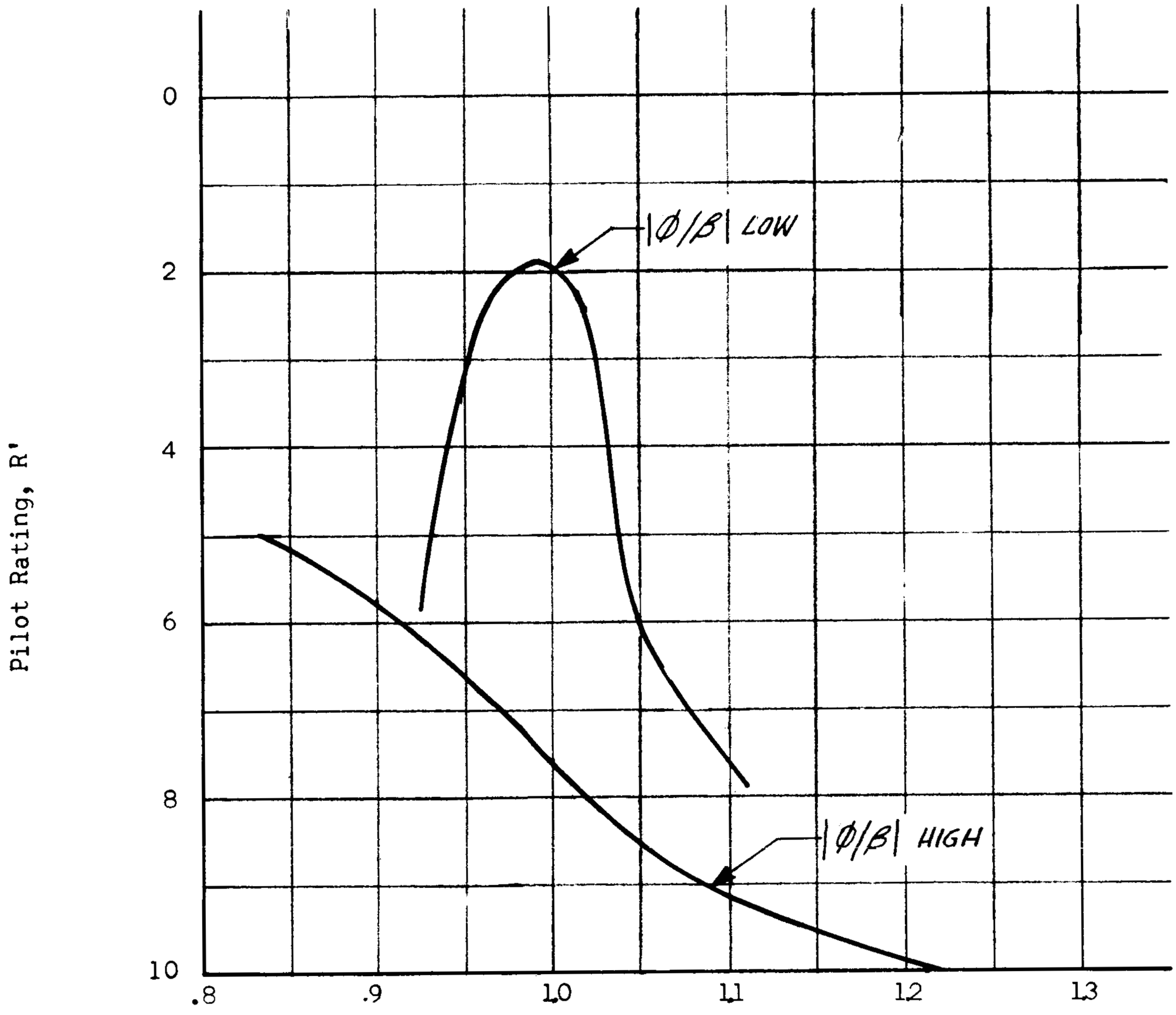


Figure 7-11
Trend of Pilot Rating, with
ω_ϕ/ω_d for High and Low $|\phi/\beta|$

Further, $\omega_\phi/\omega_D > 1$ is unsuitable in either circumstance. Let us apply the above criteria to the now obsolete Boeing 733 SST design at the transonic climb flight condition. The parameters of interest are as follows:

$|\phi/\beta| = 2$, which is small

$\omega_\phi/\omega_D = 0.81$, which is close to 1.0

$T_R = 3$ seconds, which may be a little slow

$\delta_\phi = 0.085$, which is small

$\delta_D = 0.054$, which is small

$\omega_\phi = 1.24$, $\omega_D = 1.54$, both somewhat greater than $1/T_R$

The above data meet the criteria quite well when considering the roll axis alone, except that T_R should be smoewhat smaller. A roll control loop closure around this aircraft will produce the dynamic characteristics illustrated by the root loci of figure 7-12. However, a pilot assessment of the lateral dynamic characteristics would rate it unacceptable at this flight condition because of the extremely low dutch roll damping. In this case, dutch roll damping is easily improved with yaw axis stability augmentation. The yaw axis root locus plot is shown in figure 7-13 for a yaw axis damper with a 5-second washout. Notice that the washout or an equivalent compensation is an absolute necessity to prevent the augmentation system from "fighting" the pilot in turns.

With the yaw axis accounted for, let us go back and re-evaluate the roll axis criteria. The ϕ/δ_a transfer function root locus plot is shown in figure 7-14. Due to lateral axis coupling, the roll axis looks quite different than in figure 7-12 because of the yaw axis augmentation. In particular, all second-order poles and zeros exhibit good damping characteristics. A pilot flying this vehicle would not be concerned about ω_ϕ/ω_D because the dutch roll is well damped. Furthermore, ω_ϕ/ω_D has really no meaning because the yaw axis loop closure has introduced an additional mode resulting in two second-order poles. In addition, a simple lagged roll response, described by T_R, no longer exists as such because of the additional dominant roll modes introduced.

It is usually quite difficult to obtain good lateral dynamic performance in most modern aircraft without a yaw damper operated through the rudder (or rudders). In high performance aircraft, a yaw damper alone is often not adequate. For some conditions, usually those at the higher angles of attack, a roll damper is the more effective means of damping the dutch roll oscillations. The simultaneous use of both yaw and roll dampers can yield excellent lateral handling qualities. Indeed many of the current jet transports that are equipped with yaw dampers can achieve a significant improvement in their lateral handling characteristics at the approach conditions if they had roll dampers. The problem

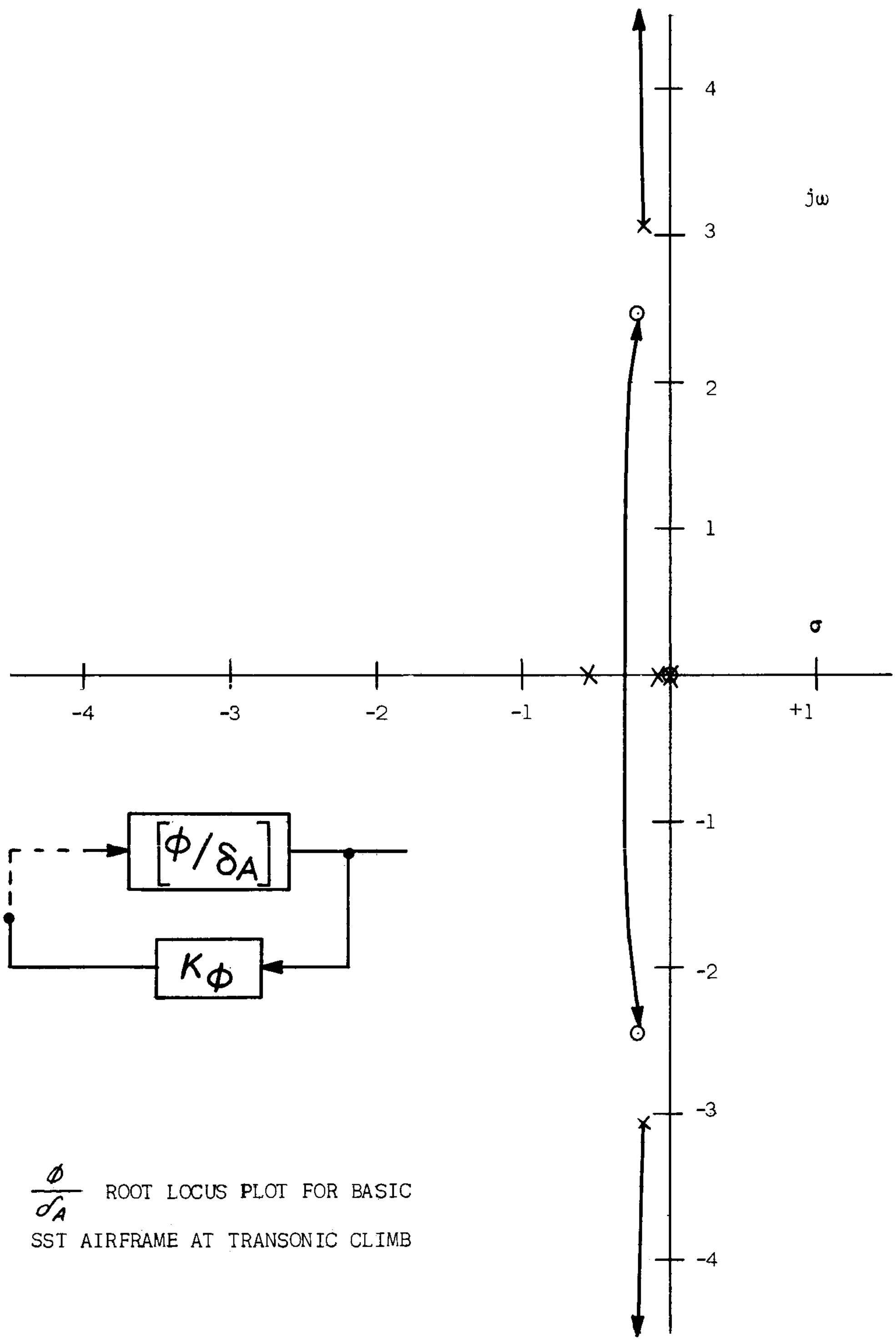


Figure 7-12
ϕ/δ_a Root Locus Plot for Basic
SST Airframe at Transonic Climb

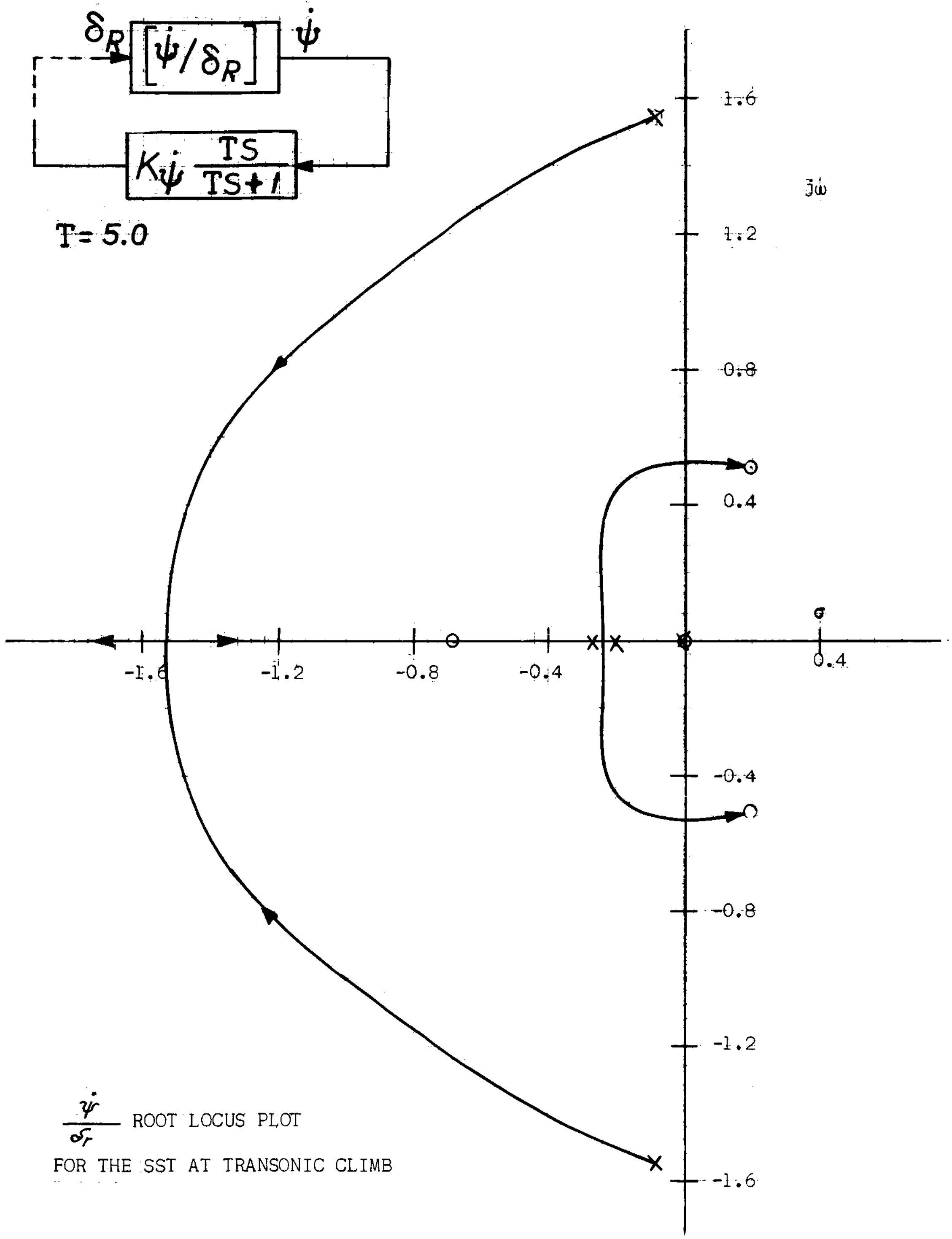


Figure 7-13
$\dot{\psi}/\delta_r$ Root Locus Plot for the
SST at Transonic Climb

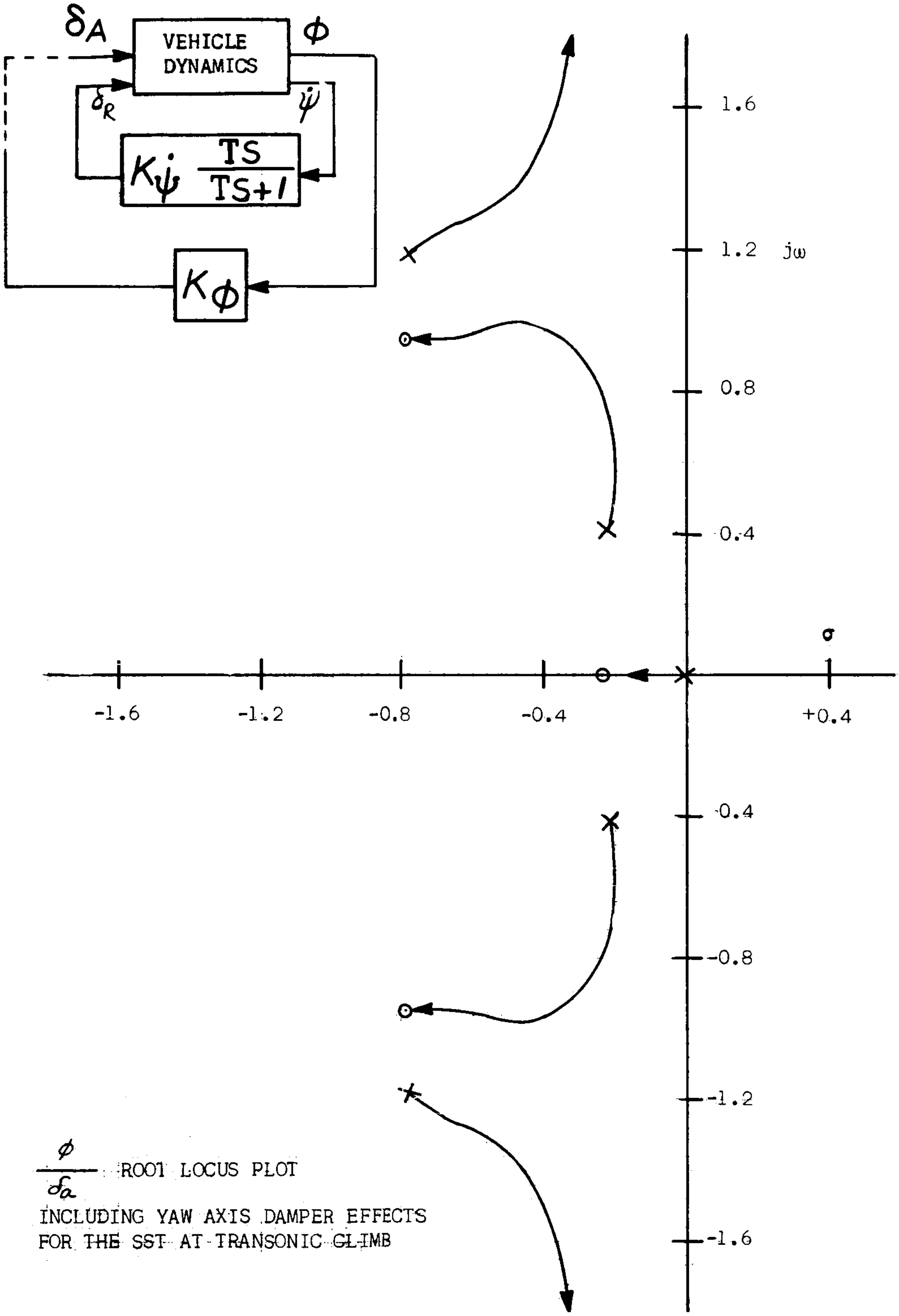


Figure 7-14
ϕ/δ_a Root Locus Plot Including
Yaw Axis Damper Effects
for the SST at Transonic Climb

is compounded by the fact that some of the current aircraft do not employ their yaw dampers during final approach. The situation for the SST, however, is much more promising. All SST designs thus far have been committed to the full-time use of ultrareliable roll and yaw dampers. If the yaw damper also included a turn coordination capability, excellent lateral handling qualities can be achieved.

D. CONCLUSIONS

1. Characteristics of an SST which make it a potentially difficult aircraft to handle in its approach and landing are as follows:

- Somewhat higher approach speeds than current jets (cut decision times)

- Larger aircraft inertias resulting in a slower attitude and flight path change capability

- Relatively large pitch control surfaces resulting in a significant normal acceleration reversal effect during pitch maneuvers

- Unaugmented lateral dynamics which are not adequate for precision approach flight path control

- Location of the pilot about 54.86 meters (180 feet) forward of the landing gear providing a poor visual reference for touchdown control and runway steering. It is also significantly forward of the cg and consequently contributes to a possibility of erroneous interpretation of acceleration cues.

2. A Command Augmentation System rather than the conventional Stability Augmentation System should be used to compensate for inherent sluggish longitudinal response. Such a system uses signals from the pilot's control column (force or position sensors) in conjunction with aircraft motion sensors (gyro and accelerometers) to shape the aircraft's response in accordance with desired criteria. The intent of such a system is not to make the SST respond like a fighter aircraft. Handling quality criteria that specify a relatively high short period pitch natural frequency are not applicable to large transport aircraft.

3. Direct lift control has a potential application in the SST as a means of cancelling the transient normal acceleration reversal effect produced by the pitch control surfaces. This can improve longitudinal handling characteristics, but at the expense of an additional flight control subsystem and its associated reliability hazards.

4. SST's will probably be equipped with full-time, fail-operational yaw and roll dampers. The yaw damper should include an automatic turn coordination

function. This should provide lateral control characteristics that are superior to those of present day jet transports. Better lateral steering on the final approach path will therefore be possible with the SST.

5. Automatic landing systems can profit from the availability of a more stable airframe resulting from the full-time lateral dampers. This permits better lateral steering control for automatic as well as manual landing. The higher aircraft inertias cause a slower flight path change capability. This cannot be compensated by Command or Stability Augmentation Systems. This characteristic will necessitate higher flareout altitudes and cause a tendency toward a larger dispersion of runway touchdown points.

SECTION VIII

ELECTRONIC FLIGHT CONTROL SYSTEM CONFIGURATIONS

A. INTRODUCTION

This section discusses various electronic flight control configurations applicable to the SST. The electronic flight controls encompass the functions of Stability Augmentation System (SAS), Autopilot System (APS) including autopilot control and flight director display computation, and Electronic Command System (ECS) that provides manual control computation. It is shown that the electronic control configurations and overall control system complexity and reliability are to a great extent determined by the basic manual control system configuration. Since the electronic flight control systems are essential to the automatic landing mission, it is important that the integration task consider the characteristics of the manual controls.

B. BACKGROUND INFORMATION

Prior to the introduction of the current jet transports, the need for electronic control systems for other than pilot relief could be seriously questioned. Advancements in flight control technology were primarily demanded by military aircraft and/or space applications where increased automation and reliability were required for mission success. At the present time, however, the rapid expansion of commercial air transportation has introduced avionics requirements that have overtaken military demands in many areas. Traffic congestion, the anticipated economics afforded by an all weather landing capability, and the apparent advantages of minimizing trip time have coupled and interacted to sponsor advancements in the state of the art of commercial electronic flight control systems.

The needs are clearly defined and the intuitive and obvious solutions are often available, but the solutions are not readily accepted. As in the past, time and education are required to gain acceptance through experience of any change in control system philosophy. The concept and need for power actuation devices between the pilot and the control surfaces can be cited as an example. Interim solutions involving aerodynamic boost or tab control delayed the application of hydraulic power controls. Only when it was found that pilots could no longer physically cope with the control power requirements did the operators accept and rely upon powered controls. There were compromises, of course. Hydraulic systems became more complex and maintenance difficulties were experienced, but the use of powered controls was no longer challenged.

Automatic control for pilot relief and Stability Augmentation Systems (SAS) providing increased damping were readily accepted because the pilot still had control in two ways. He could either use or not use these functions and, while taking advantage of the function, still maintain complete control of the aircraft through the manual controls. Stability Augmentation Systems have traditionally been of limited authority. They operate in series with the pilot inputs such that any failures can be compensated for by manual inputs. Aircraft have been designed to have acceptable (but marginal) dmaping without SAS. Handling qualities have been brought to an acceptable level by addition of complex and heavy mechanical pneumatic or hydraulic-feel systems. Automatic path and pilot relief type control inputs have been traditionally introduced in parallel with pilot manual inputs. They are given limited force authority so that the pilot can overpower automatic inputs with relatively low force levels. Thus, the commercial pilot's authority has not been seriously challenged to date by dependence on automatic control.

Aerodynamic design problems associated with providing economical flight performance in the latest jet transports have forced reliance upon Stability Augmentation Systems to a limited degree. Thus, the Boeing 727 aircraft has dual rudder surfaces driven by dual SAS computers and the loss of one of these systems results in restricted and less economical flight operation. In addition, the 727 design anticipated the requirement for low level operation under automatic control. It provided for dual, independent, mechanically limited, automatic fail-safe control of the landing phase. Automatic control is still of limited authority and easily overpowered at the discretion of the pilot at relatively low force levels applied at the column. The feel system, in order to provide acceptable handling qualities for manual control and to ensure that the autopilot authority is properly controlled, is very complex; but it is considered reliable.

In summary, as the demands for automatic control have grown, increased emphasis has been placed upon design of complex feel and mechanical control systems. The concept of automatic control has been recognized, but in a roll which imposed additional design constraints and increased the complexity of the basic manual controls.

One might observe that the manual control complexity is in direct proportion to the lack of confidence in the reliability of the electronic controls. Historically, this lack of confidence can be rationalized. However, if we extrapolate electronic reliability to its predicted potential, the mechanical and hydraulic devices represent the greater reliability hazard. The questions which must be answered at any time when a flight control system design is undertaken are: How much can one depend upon predicted reliability of electronics, and how great a departure from conventional philosophies will be accepted? Different designers weigh these problems differently at any given time. This can be illustrated by a review of approaches taken by three SST design groups at Lockheed, Boeing, and Sud BAC. The method of integrating the manual and automatic controls with the control surface actuators have been different for the three SST aircraft identified with these manufacturers. It should be emphasized that the configurations cited in the following discussion are not necessarily the final configurations that would be committed by these manufacturers to production aircraft. Table 8-1 summarizes the number of hydraulic actuators employed in the three different approaches for positioning control surfaces. The number varies from 78 for a recent Boeing design to 11 for the Concorde. Note that dual tandem or triplex tandem actuators have been counted as single actuators.

TABLE 8-1
ACTUATOR SUMMARY
(ALL AXES)*

Manufacturer	Parallel Actuators		Series Actuators	Surface		Total
Lockheed SST	12	6 Triplex tandem boost plus 6 Autopilot integrated	9	43	24 Elevon 18 Rudder	63
Concorde SST	3	Dual tandem electro-hydraulic	0 (Electrical signals to directly to surface actuators)	8	Dual tandem electro-mechanical	11
Boeing SST	12	6 Boost plus 6 Autopilot integrated	9	57	6 Stabilizer 3 Rudder 12 Spoiler 24 Flaperons 6 Ailerons 6 Stabilizer flaps	78

*Trim, feel, and dwell servos for programming linkages, wing position, etc, not included.

First, let us review the requirements for automatic or electronic control as recognized by all major SST suppliers in common. The following requirements exist for at least a major part of the SST mission:

1. A Stability Augmentation System (SAS) is required in at least two axes to damp the short period oscillations of the aircraft. Based on present system reliability technology, a fail-operational, fail-safe system characteristic is demanded in the electronic implementation to meet mission reliability requirements.

2. An Automatic Flight Control System (AFCS) to provide for climb and descent profile control, cruise control, and automatic landing control is required. A minimum of fail-safe failure characteristics, and in the case of

automatic landing, a fail-operational, fail-safe failure characteristic based upon safety requirements and present electronic system reliability technology is demanded.

3. An Electronic Command System (ECS) (some form of fly-by-wire) is required to augment the basic manual controls to cope with the suspected inadequacies of conventional mechanical hydraulic manual controls for long flexible aircraft. (Pure mechanical-hydraulic or electrohydraulic-feel systems and transmission of manual inputs to control surface actuators are considered inadequate and depended upon only for the emergency manual control mode.)

C. CONTROL SYSTEM MECHANIZATION PHILOSOPHY

The following is a brief description of Concorde (Sud), Lockheed, and Boeing control approaches. Details of the actuator and data transmission implementations are given in Appendix A. These three basic flying control mechanization philosophies are illustrated in figures 8-1, 8-2, and 8-3. The Concorde System, figure 8-1a and b, is characterized by simplicity of design. The partition principle of redundant surface control is utilized (figure 8-1a), three sets of elevons and two rudders. Referring to figure 8-1b, each surface is controlled in a redundant fashion by two electrohydraulic links and a backup mechanical-hydraulic link. In operation, one electrohydraulic link is used as primary, with the second available in case of failure. Following failures of both electrohydraulic links, the mechanical-hydraulic mode is activated. This sequence of control reversion coupled with the redundant surfaces affords a high mission reliability. The unique features of the Concorde design, in addition to primary manual control through fly-by-wire, lies in the integration of the Stability Augmentation and Automatic Flight Control System functions. No additional hydraulic actuators are utilized. The surface power controls and boost actuators, which are both dual tandem, are fitted with electromagnetic torquers. The SAS electronic surface command signals are added to the pilot's manual control electrical commands to the surface power actuators. The autopilot signals are introduced through the boost actuators of the backup mechanical-hydraulic servos to the control surfaces. The resultant system, while being more complex in terms of manual control over the conventional dual tandem mechanical-hydraulic system, is less complex than many current redundant systems when SAS-APS functions are introduced.

In contrast, let us consider one configuration proposed by Lockheed (figure 8-2a and b). Here, the number of control surfaces are increased; four versus three sets of elevons and three versus two rudders (as shown in figure 8-2a). The greatest difference, however, lies in the redundancy philosophy. Lockheed anticipated a greater need for redundancy than Sud Aviation (figure 8-2b). First, two independent mechanical-hydraulic links to the control surfaces (pilot and copilot) are maintained similar to present day, mechanical-hydraulic systems.

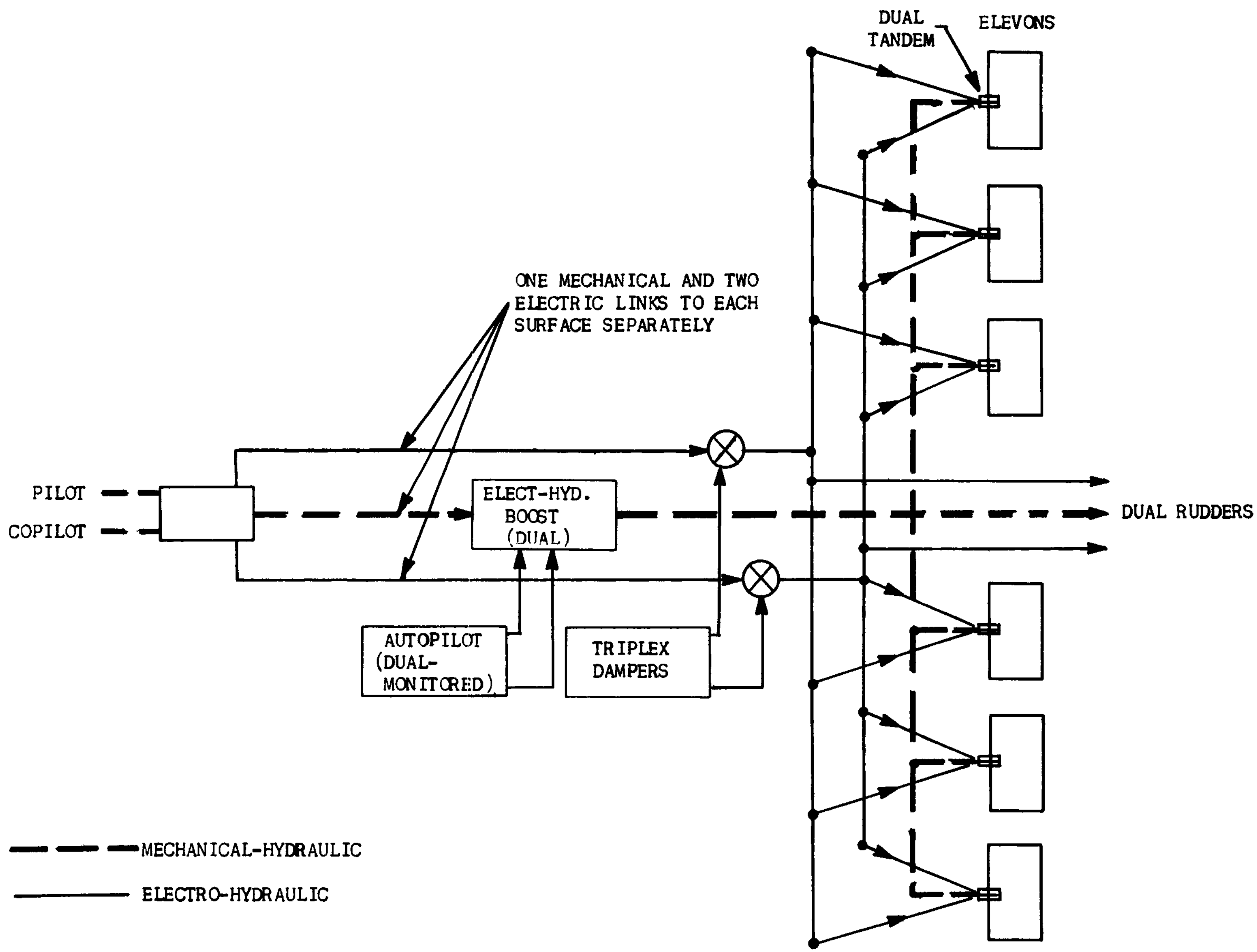


FIGURE 8-1a CONCORDE FLYING CONTROLS - GENERAL ARRANGEMENT

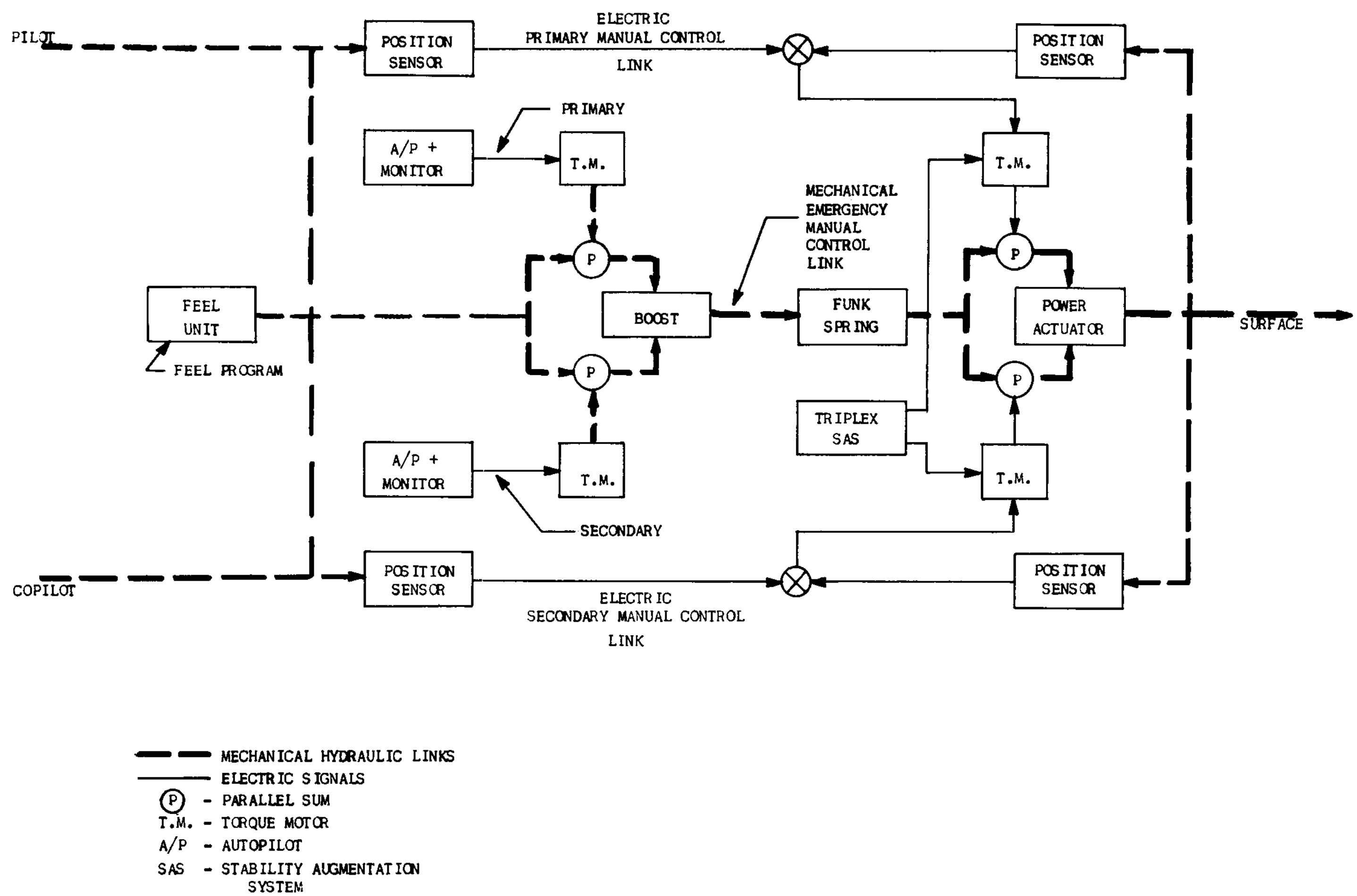


FIGURE 8-1b SUD - CONTROL SYSTEM PHILOSOPHY (CIRCA 1965)

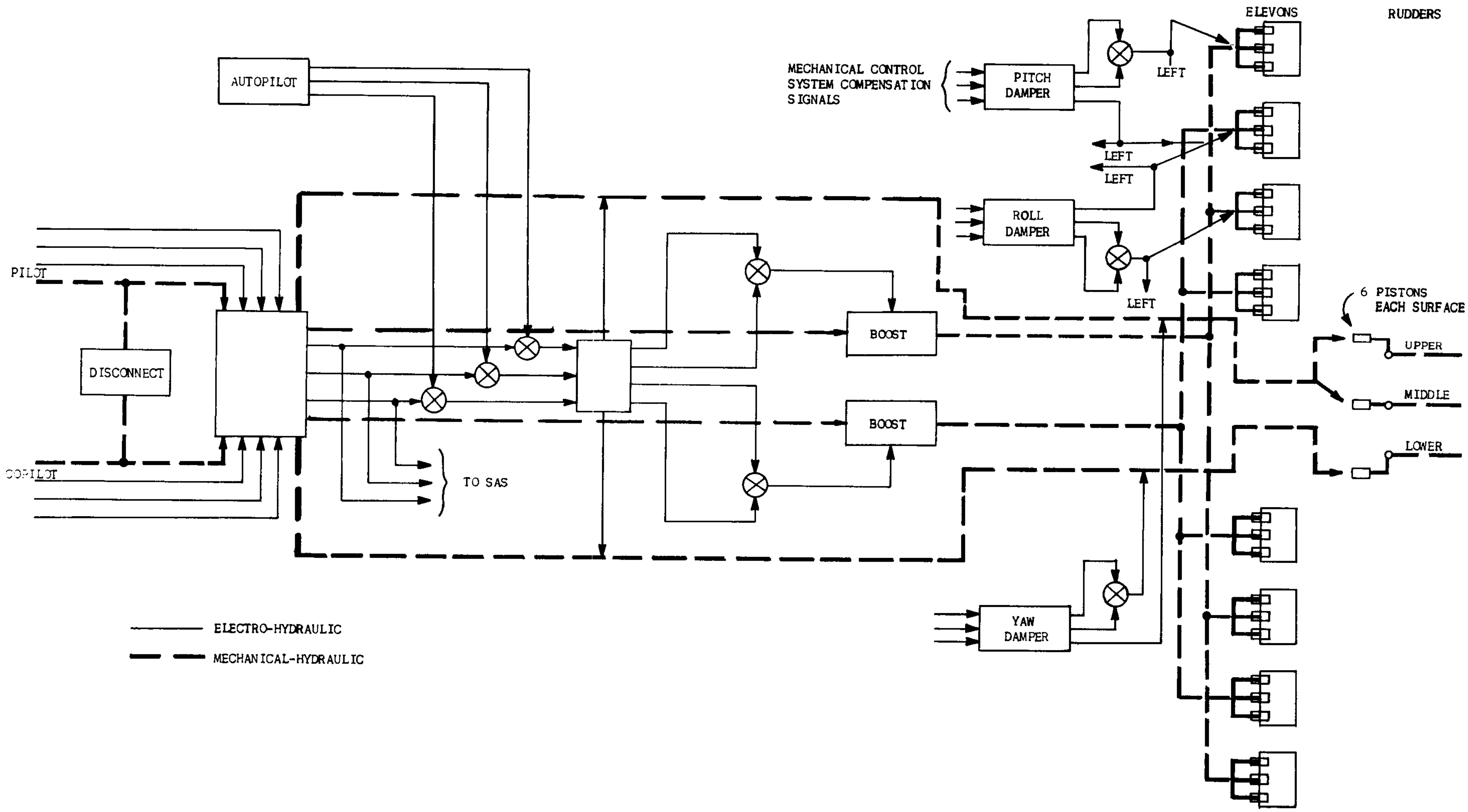


FIGURE 8-2a LOCKHEED SST FLYING CONTROLS - GENERAL ARRANGEMENT (CIRCA 1965)

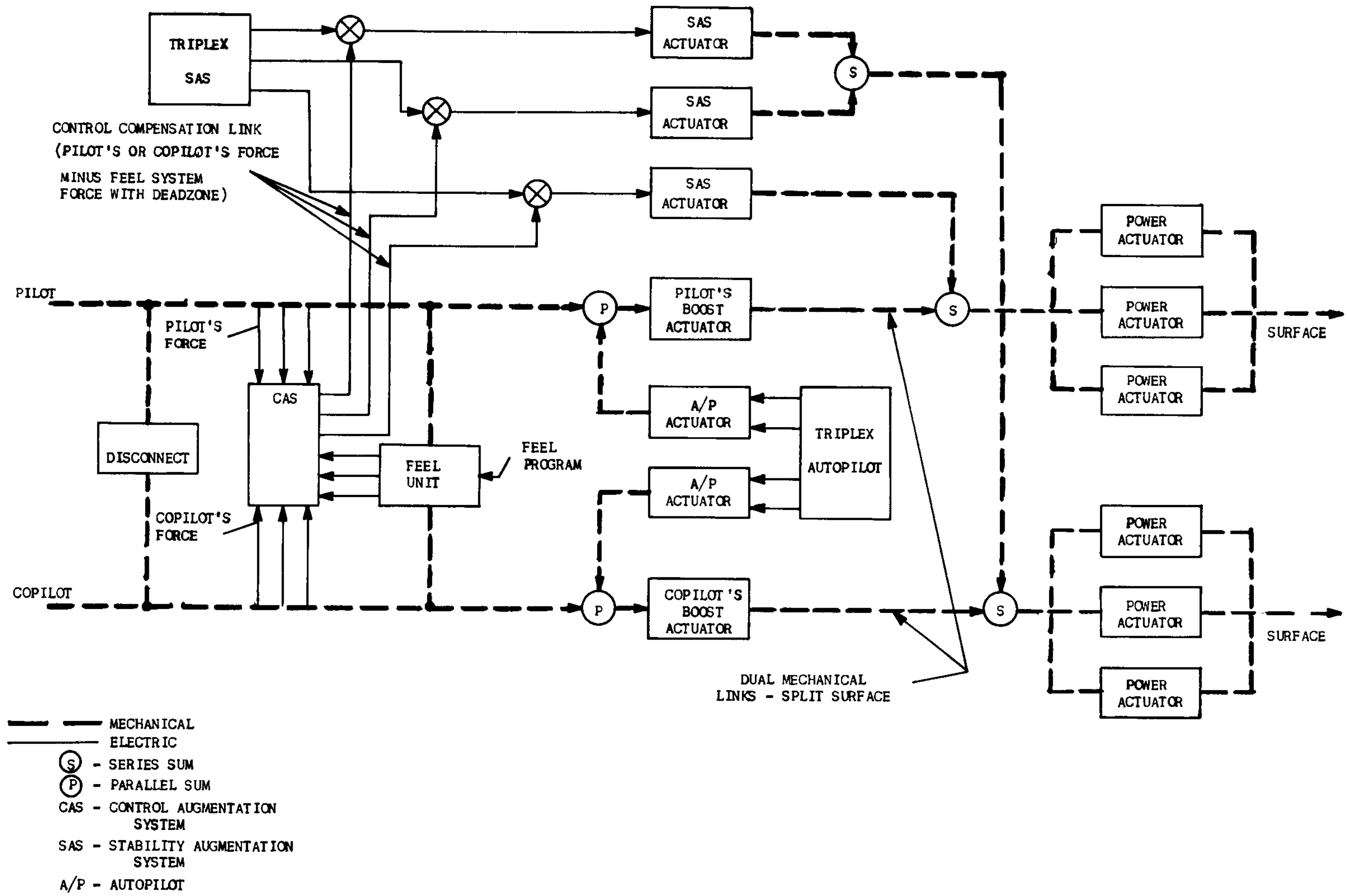


FIGURE 8-2b
LOCKHEED - CONTROL SYSTEM PHILOSOPHY (CIRCA 1965)

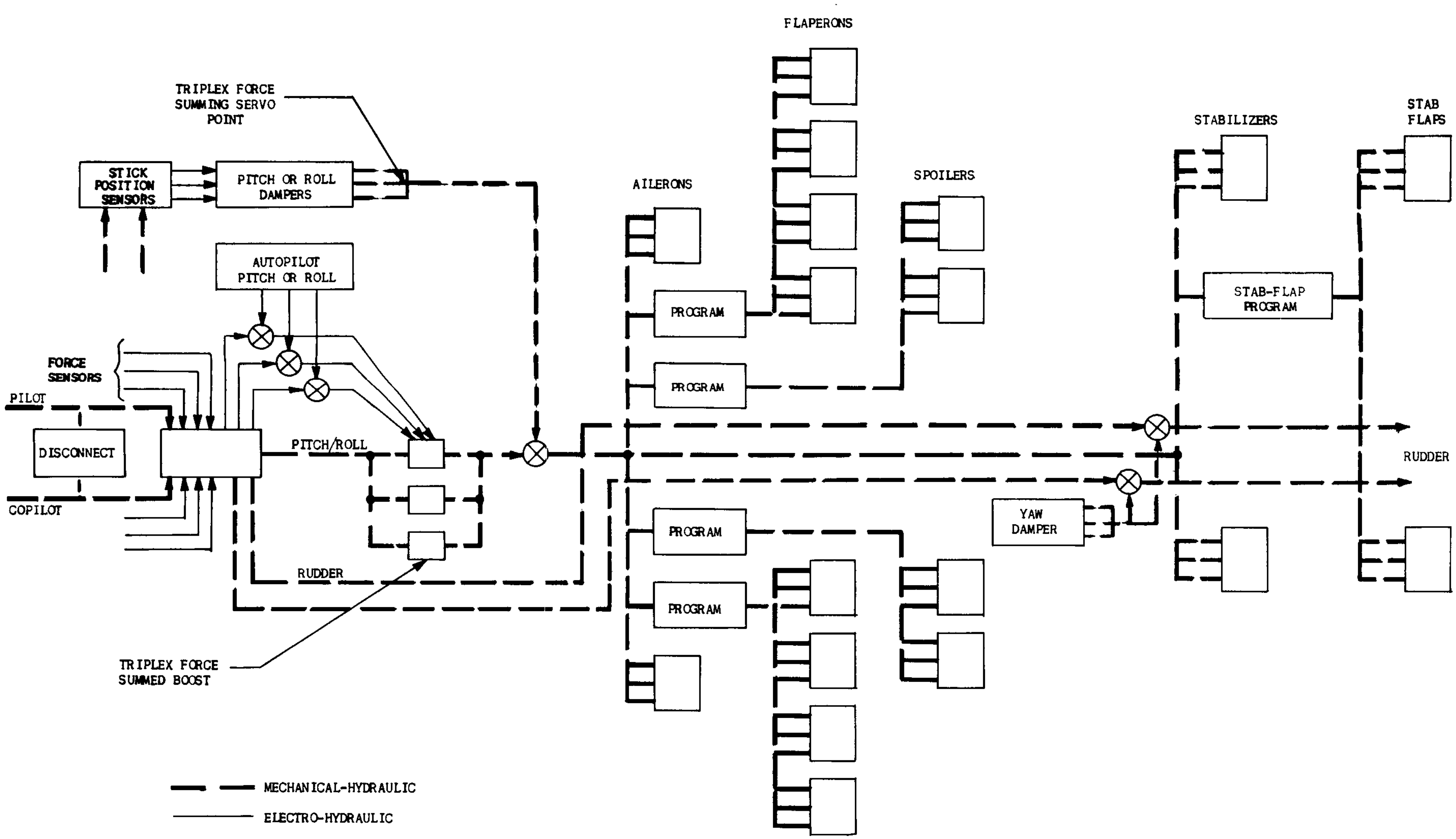


FIGURE 8-3a BOEING SST FLYING CONTROLS - GENERAL ARRANGEMENT (CIRCA 1966)

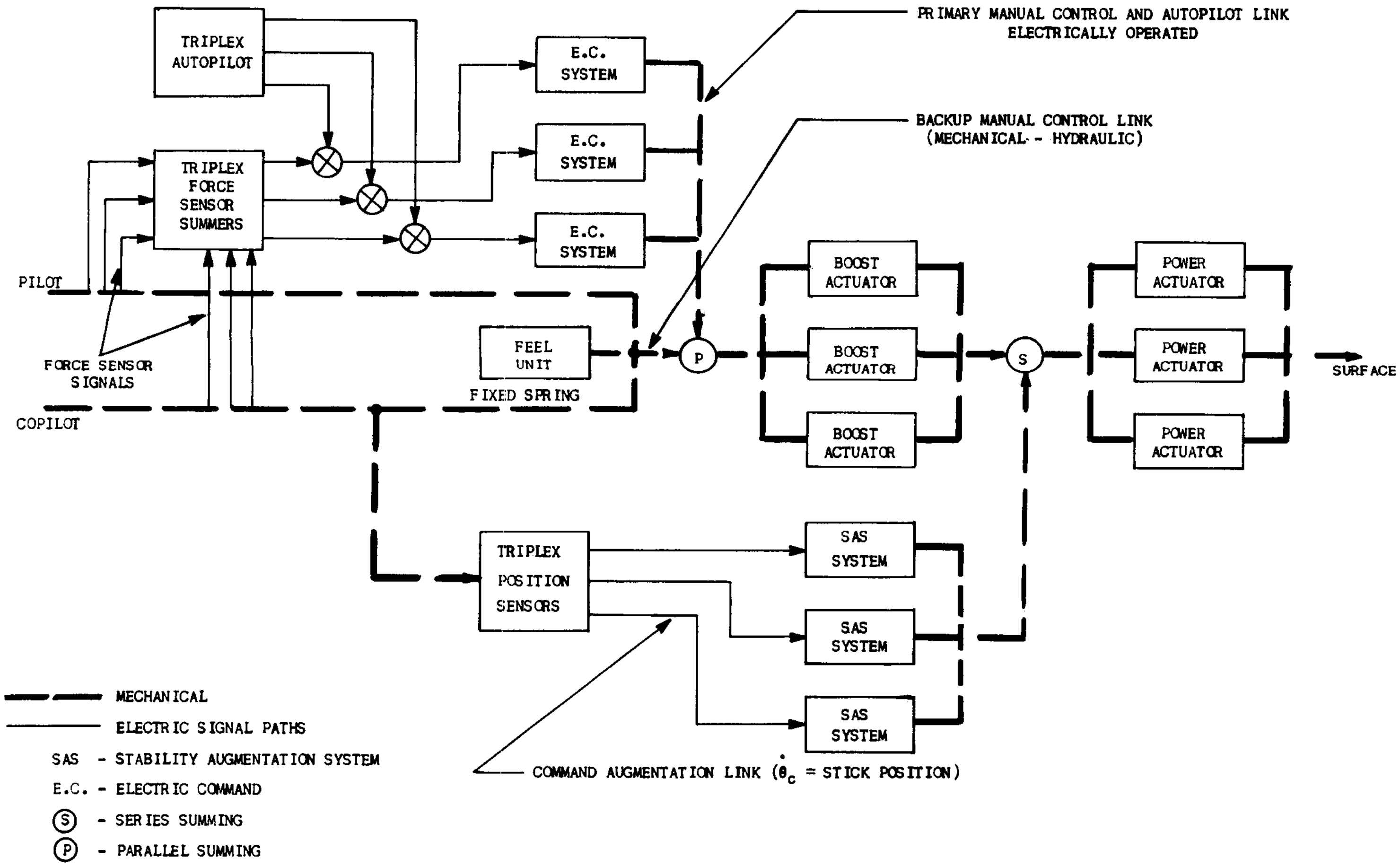


FIGURE 8-3b BOEING - CONTROL SYSTEM PHILOSOPHY (CIRCA 1966)

Second, since multiple surfaces are employed, a choice is made to divide the surfaces between the pilot and copilot. In the primary manual control mode, pilot and copilot sticks are connected such that all surfaces are controlled by either pilot. Upon disconnect at the option of the crew, surface control is split. Next, each control surface is driven by triplex mechanical-hydraulic actuators versus dual actuators in the Concorde. Pilot or copilot manual control inputs are boosted by triplex tandem actuators which exercise the control valves of the surface actuators. In addition, since the mechanical-hydraulic links are suspect in terms of friction and dead spot, the primary manual mode relies upon triplex electrohydraulic links utilizing nine additional SAS actuators (triplex yaw, roll, and yaw SAS actuators) which supply mechanical inputs to the surface actuators. Thus, the primary manual control mode is dependent upon triplex surface actuators, triplex tandem boost actuators, and triplex electrohydraulic SAS actuators (prior to first failure) as opposed to the Concorde which utilizes one-half of a dual boost and one-half of a dual tandem power actuator per surface.

Additional complexity is encountered in the philosophy of integration of the automatic control commands with the manual control system. SAS signals are introduced through the triplex sets of series actuators which are also employed to augment manual control. Triplex automatic control inputs are introduced through independent dual sets (pilot and copilot) of autopilot actuators. Thus, 12 additional actuators are employed for APS commands and nine actuators for SAS in addition to the triplex split surface control system employed for manual control.

The Boeing system, illustrated in figure 8-3a, appears as complex as the Lockheed design. However, this impression is largely the result of the aircraft design and not so much the control system philosophy. More surfaces are required due to the variable sweep wing design. Instead of elevons and rudders, the Boeing SST uses rudders, stabilizers, spoilers, flaperons and ailerons. The control system philosophy is relatively simple, as shown in figure 8-3b. Pilot and copilot control columns control all surfaces and are coupled in the normal manual mode. Provisions for disconnect are made. Each control surface employs triplex mechanical-hydraulic actuators, as in the Lockheed design. The control surface actuators are commanded by either triplex sets of stability augmentation actuators or triplex sets of boost actuators. The triplex sets of boost actuators are commanded either by triplex sets of force summing Electronic Command Actuators (ECS) or directly by manual control inputs. In the primary manual pitch roll control mode, electronic fly-by-wire control is exercised through the ECS actuators, through the boost actuators to the surface actuators (backed up in case of failures by the direct mechanical link to the boost actuators), and augmented by the series SAS actuator inputs to the surface control actuators. It is interesting to note that this control philosophy, despite the increased number of control surfaces does not suffer proportionally to the Lockheed design (78 versus 63 actuators for 19 versus 11 control surfaces, respectively).

The Concorde design represents an attempt at the utmost in simplicity and yet appears to afford a mission reliability consistent with state-of-the art advancement. The Lockheed design represents a conservative approach to cover all contingencies or doubts. The Boeing design represents a compromised conservative approach coupled with an attempt to advance the state of the art of redundant system design in terms of failure transient effects (force summing servos).

Of the three designs described, the Concorde approach attempts to meet increased reliability and safety objectives with the simplest although somewhat compromised design. Yet, a simpler design is possible if the automatic control signals could be introduced in series through the SAS channels directly to the control surfaces. Since electrohydraulic control is admitted as a basic requirement for manual control, why should this link be ignored for automatic control? This is a philosophical question which can only be answered as a function of time. Traditionally, automatic control has operated in parallel with pilot inputs; that is, the stick moves in response to autopilot commands. This pilot's ability to monitor the performance of the autopilot is based to some extent on his interpreting the control stick motions. For example, in an automatic landing, the pilot anxiously waits for the first signs of flareout initiation by anticipating the backward movement of the control stick. Indication that flareout has commenced is also provided in the form of progress annunciator displays. Would a pilot be content to monitor automatic system performance by observing progress annunciators and failure warning displays? This is both doubtful and perhaps undesirable. The most skilled pilots are alert to idiosyncrasies of the autopilot controls and can often interpret performance anomalies before failure detection equipment can identify a malfunction. In the present era, when major new demands are being imposed on the automatics, there may be some advantage to providing the pilot with the additional information regarding what the autopilot is actually doing. However, after several more years of experience and acceptance of the larger role of automatic controls, the all series autopilot may be introduced without too much controversy. Indeed, the military has been accepting series autopilots with limited authority for some time. Here, the trend is to open up the authority limits. Full authority series autopilots and all fly-by-wire controls are expected to eventually become state of the art. At that time, major simplifications in an aircraft's flight controls will be attainable.

D. IMPLICATIONS OF SST ELECTRONIC FLIGHT CONTROLS ON ALL WEATHER LANDING SYSTEMS

1. The SST primary flight controls will depend upon electronic command systems to transmit control information to the surface actuators. Both the autopilot and the manual inputs are transmitted through essentially the same electronic and electrohydraulic links.

2. These primary flight control electronic and electrohydraulic linkages are configured for fail-operational capability. They all make provision for interfacing with triplex autopilots. The inclusion of the automatic landing modes within the autopilot will therefore provide an inherent fail-operational automatic landing system if the necessary sensor redundancy structure is also provided.

3. Questions regarding reliability advantages of manual versus automatic landing techniques become irrelevant in an aircraft that is totally committed to electronic primary controls for precision flight. Most of the complexity and reliability hazard of the automatic system will also be in the path of the manual inputs.

SECTION IX

INTEGRATED DIGITAL AVIONICS

A. INTRODUCTION

The airborne digital computer looms as the major element of future automatic flight control systems, but the rationalizations for its use are often misunderstood. In the 1967 state of the art of commercial transport avionics, the airborne digital computer has found its most significant application in the Inertial Navigation Systems. Other aircraft subsystems employ so-called digital techniques, but these do not involve the general purpose computer that represents the maximum potential of digital technology. Most of today's automatic flight control devices use analog control techniques with special purpose digital logic systems.

To many controls engineers, the most impressive aspect of the digital computer seems to be its computation power and versatility. This viewpoint often leads to an erroneous perspective of a digital flight control system. The tendency is to study methods of implementing digital control laws for the autopilot function. The fallacy of such an approach is the minor role the control law function plays in autopilot avionics. This is illustrated in figure 9-1 that shows the relative complexity of the various functions that comprise an electronic flight control system. It is seen that control law computation is a very minor part of the electronic flight controls. It ranges from such utterly simple devices such as summing resistors that provide the variable weighting of the different feedback terms to relatively complex, active compensators. Thus, if our rationalization to use a digital computer in an autopilot mechanization is the desire to use its computation capability, we would replace only about 5 percent of the more conventional analog autopilot with a digital computer. The signal processing and power amplification for driving actuators and level changing for operating power switches, annunciators, etc, would obviously still be required. Indeed, the signal processing equipment required to interface the input and output devices with a digital computer can be more complex than the entire analog autopilot.

If the airborne digital computer does not fare well in a complexity tradeoff with the analog mechanization of electronic flight control systems, why is it viewed with such keen interest and enthusiasm by the aviation industry? The answer to this question does not appear in a comparison with the more sophisticated of present day autopilots. It appears when we consider the possibilities of automating flight control functions and noting that present day automatic control loops do not really represent automation. The tasks of selecting control modes, setting reference points, tuning radio navigation devices, monitoring many instruments for status descriptions and warning indications, and operating

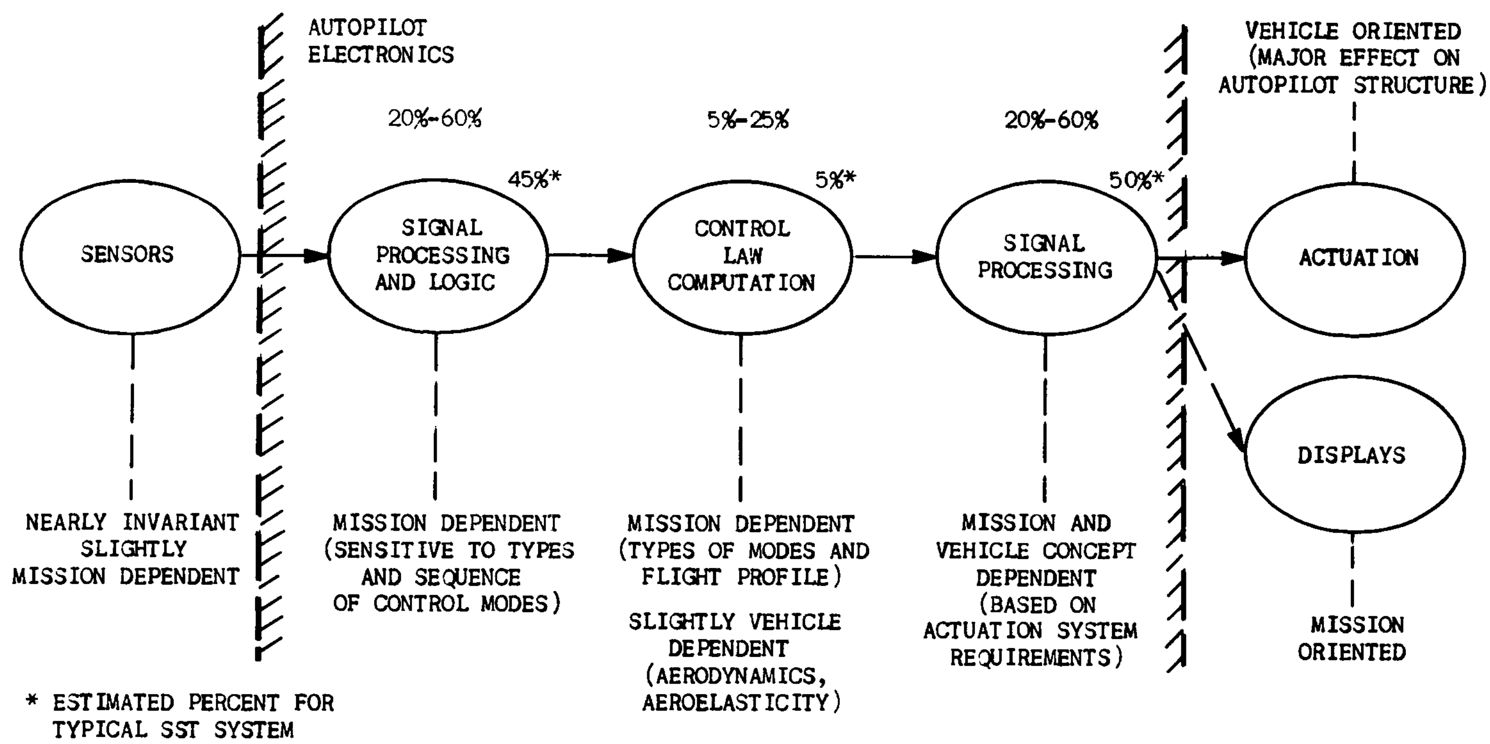


FIGURE 9-1 ELECTRONIC FLIGHT CONTROL SYSTEM FUNCTIONS - RELATIVE COMPLEXITY

various manual controls in precisely timed sequences are major pilot chores. They become especially pressing during blind landing operations. The substitution of some automatic for manual controls in all weather landing procedures has not truly relieved the pilot of his workload. It has replaced some of the human servomechanism functions, but has increased the visual workload associated with monitoring instruments, indicators, and devices, and increased the task of setting dials, etc. An automated landing flight control system would be one that performs the multitude of data input, mode control, and sequencing operations after receiving a single instruction from the pilot. To achieve this level of automation, the programming and data storage capability of the general purpose digital machine is essential. Present day electronic flight control systems can perform a variety of sophisticated control tasks, but they are not compatible with the concepts of inserting a data card corresponding to the landing airport and thereby initiating the entire sequence of actions required to guide and control the aircraft to touchdown. It is only with this level of automation that the pilot can truly assume the role of systems manager.

The discussions which follow consider the organization of avionics subsystems needed to achieve automated landing flight controls. The problem is obviously not solved merely by installing and programming a digital computer. That computer must have a two-way communicating interface with many sensing and control subsystems. This differs from the present state of the art where communication paths are essentially one way; that is, from the sensors to control computers. In the automated system, the computer must have the capability of addressing and controlling the sensors. For example, it should be able to initiate sensor self-tests, remotely select navigation receiver channels, set the aircraft's heading or other flight path reference, and verify the completion of various control actions. This requires an extensive systems integration effort. It is this integrated digital avionics effort that is the subject of the ensuing discussions.

B. THE ANALOG VERSUS DIGITAL TRADEOFFS

The analog versus digital tradeoff study is a ritual exercise performed with increasing frequency by today's designers of electronic flight control systems. These tradeoffs compare systems on the basis of the following:

- Cost
- Size-Weight
- Complexity-Reliability
- Accuracy and other aspects of performance
- Flexibility and growth potential

Unless such studies are directed toward very specific requirements and performance objectives they tend to be superficial and hence, like many tradeoff studies, are used to rationalize a technical prejudice or intuition or to justify a previous commitment to a specific approach. It is beyond the scope of this report to conduct tradeoff studies regarding the choice of analog or digital computers for all weather landing or other electronic flight control functions. However, the trends associated with these studies will be reviewed briefly.

If we use as a baseline a 1967 transport aircraft automatic flight control system and compare analog versus digital computer implementations, the following conclusions are usually obtained:

- The analog system wins the cost, size-weight, and complexity-reliability tradeoffs.

- From the standpoint of accuracy and performance criteria, there is no significant advantage to either approach. While one would expect a digital computer to show accuracy advantages, this does not generally occur in a closed loop control application. Accuracy is usually dictated by the tightness of the control loop and the quality of the measurement data (sensors).

- From the standpoint of flexibility and growth potential, the digital approach is superior, but with reservations. The reservations are based on the fact that software flexibility is not easily achieved in a real time digital process control system. If provision is not made in the original programming for subsequent additions, then these changes are often more expensive than hardware redesigns.

Despite the better showing of the analog approach in cost, size, and complexity, the digital system often wins in these categories by virtue of an interesting machination involving the tradeoff ground rules. Here the rule is to assume that a central digital computer comes for nothing because it is already available. That is, a computer may already be onboard to perform some other function and it has excess computation capability. Thus, why not use that computer for the flight control computations? This reasoning is generally used today in the design of spacecraft control systems. The fact that the data conversion electronics required to interface the various sensors with the digital computer are usually more complex than the analog control system is also countered by a similar rationalization. Data conversion equipment employing multiplex techniques is available for other functions and hence it is also assumed to be available for the flight control functions at almost zero penalty in cost, size, or complexity.

The commitment of a digital computer to the automated landing system concept results in a similar escalation of functions encompassed by the computer. The primary justification for the digital computer is its ability to store programmed instructions in its large memory. However, once we have transmitted the process data to the computer, the computation of the control laws represents a minor addition to the program. The digital computer, then, readily encompasses the flight path steering law functions of an autopilot. These usually provide attitude command inputs to an attitude stabilization inner loop. While a moderately fast computer* has the capability of providing the attitude stabilization function, the large number of computations associated with the higher frequency attitude stabilization compensators does begin to make a significant dent on the machine's capacity. Also, the attitude stabilization functions are often intimately tied into the flow of analog control data through redundant fail-operational hydraulic servo configurations. It would be a formidable task to interface redundant digital computers with these hydraulic controls. Hence, a natural interface for the digital functions is at the attitude command point, but there are no overwhelming reasons why this interface cannot be closer to the actuation system.

In the analog versus digital tradeoffs, an interesting fact regarding terminology should be noted. The analog systems are actually hybrid configurations in that they use a digital logic structure to program the control sequences. (In an inverse sense, the digital systems are also hybrid in that their inputs start as analog signals.**) The manner in which the digital logic structure interfaces with the control laws is illustrated in figure 9-2. These logic functions are actually implemented, in 1967 state-of-the-art autopilots, with digital microcircuits. Three types of inputs are shown. They are as follows:

- Discrete commands obtained from mode selection switches, control sets, etc.

- Programming logic obtained from other functional modules, monitoring circuits, etc. These inputs are generated by such devices as threshold or level detectors, timing circuits, comparison monitors, and sequential logic equations.

- Interlock logic from mechanical status devices. These are part of a general class of enabling logic functions obtained from detent switches, mechanical travel limit switches, pressure operated switches, etc.

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*In these discussions, a moderate computer having the following minimum characteristics is assumed: Add Time - below 10 microseconds; Multiply Time - below 50 microseconds; Memory - minimum 4096 words; Word Length - 16 bits.

**The digital sensor is an elusive objective that has not been achieved because it does not really exist. There are only different techniques of analog encoding that may lend themselves to simpler digital conversion equipment. In this regard, it is noted that the variable frequency sensor that is sometimes viewed as a natural analog for digital converation actually involves more complex digital conversion electronics than is required to encode a voltage analog.

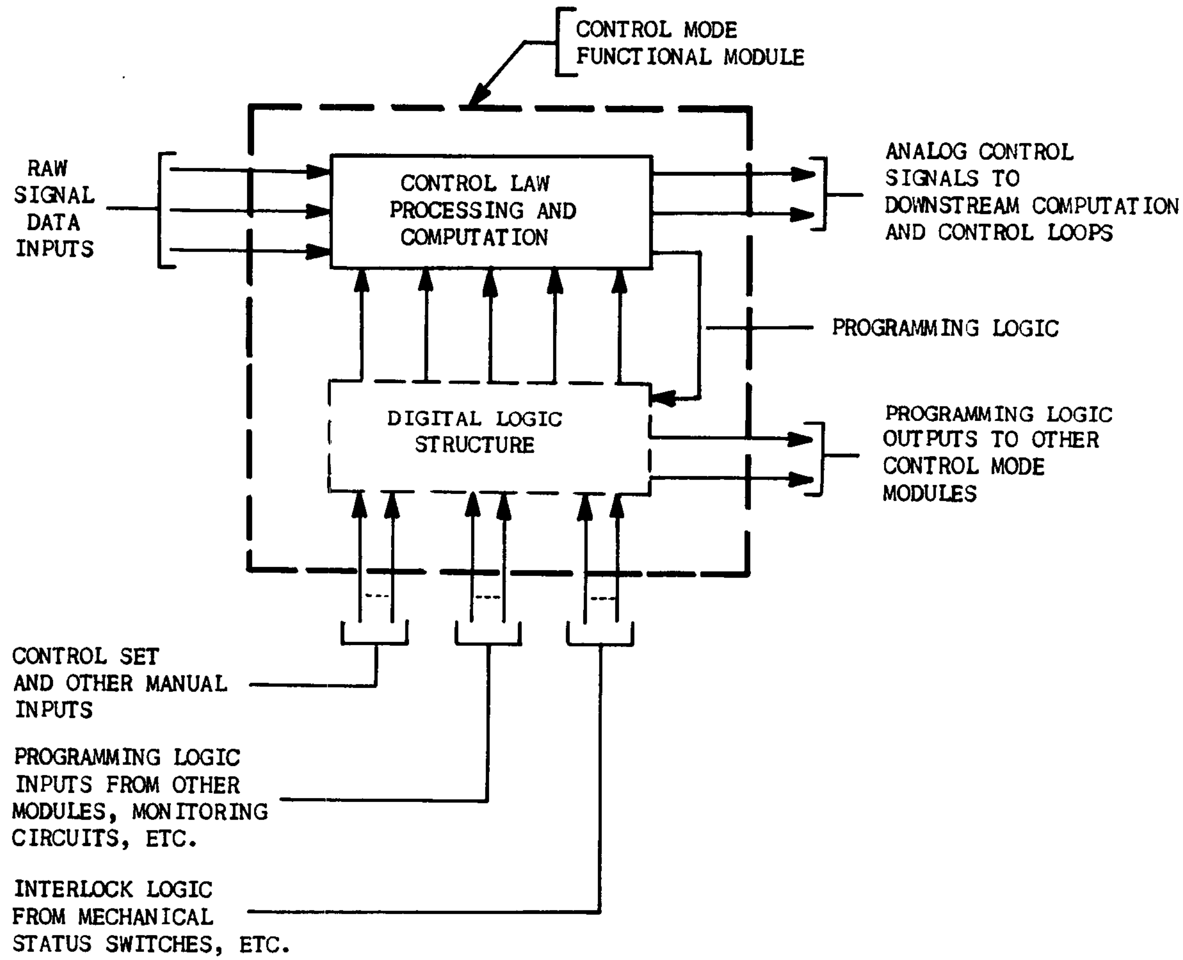


FIGURE 9-2 TYPICAL 1967 AUTOMATIC FLIGHT CONTROL FUNCTIONAL HYBRID MODULE

The operations encompassed by the digital logic structure include signal level changing from higher voltages used in aircraft interlocks to lower levels that are compatible with digital microelectronic logic circuitry. The outputs are high and low level discretes to logic circuits in other functional modules as well as the discretes that inhibit, transmit, or control the weighting of the analog control signals. The logic equations are solved in a continuous manner. The term logic structure is used to describe this function because the continuous nature of the process does indeed yield the equivalent of a physical set of interconnections through which control information is transmitted. This is in distinction to the sequential computation of the control logic functions when a flight control system is implemented with a general purpose digital computer. With the general purpose computer, the various logic inputs (shown in figure 9-2) must first be converted to the proper signal level and digital data format used for machine inputs. Then the program must, in general, sequentially scan each of the logic inputs and compute decisions every cycle time. There are variations to this scheme that might be followed. Priority interrupt lines may be used to change a logic decision only when the input status changes. This requires additional conditioning of the input data discretes so that they transmit change of status as well as status. Also, a large number of the inputs to a logic equation are those designated "programming logic" in figure 9-2. This data is obtained from the computer itself and would have to be scanned each cycle time to determine whether a change had occurred.

The point to be emphasized here is that the present day hybrid computing schemes, as illustrated in figure 9-2, are extremely efficient in their implementation of logic computations. When these computations must be performed in a general purpose digital computer, there are certain penalties. First, the consumption of computer capacity in performing these logical operations is significant for a multimode, modern autopilot system. The capacity problem is aggravated by the fact that the logic equations must be solved repetitively at a fairly high rate. Then, in order to prevent major disruptions of functions because of possible noise effects on a single input discrete, rather elaborate checking and redundant programs must be used. The result is that the logic functions that are easily implemented with physical circuitry in the hybrid system of figure 9-2 cause very difficult programming problems when implemented in a general purpose computer. This aspect of the digital versus analog tradeoff is often neglected or underestimated in hurried studies of the problem.

C. AUTOMATED ALL WEATHER LANDING AND INTEGRATED DIGITAL AVIONICS

1. Central Flight Control Digital Computer

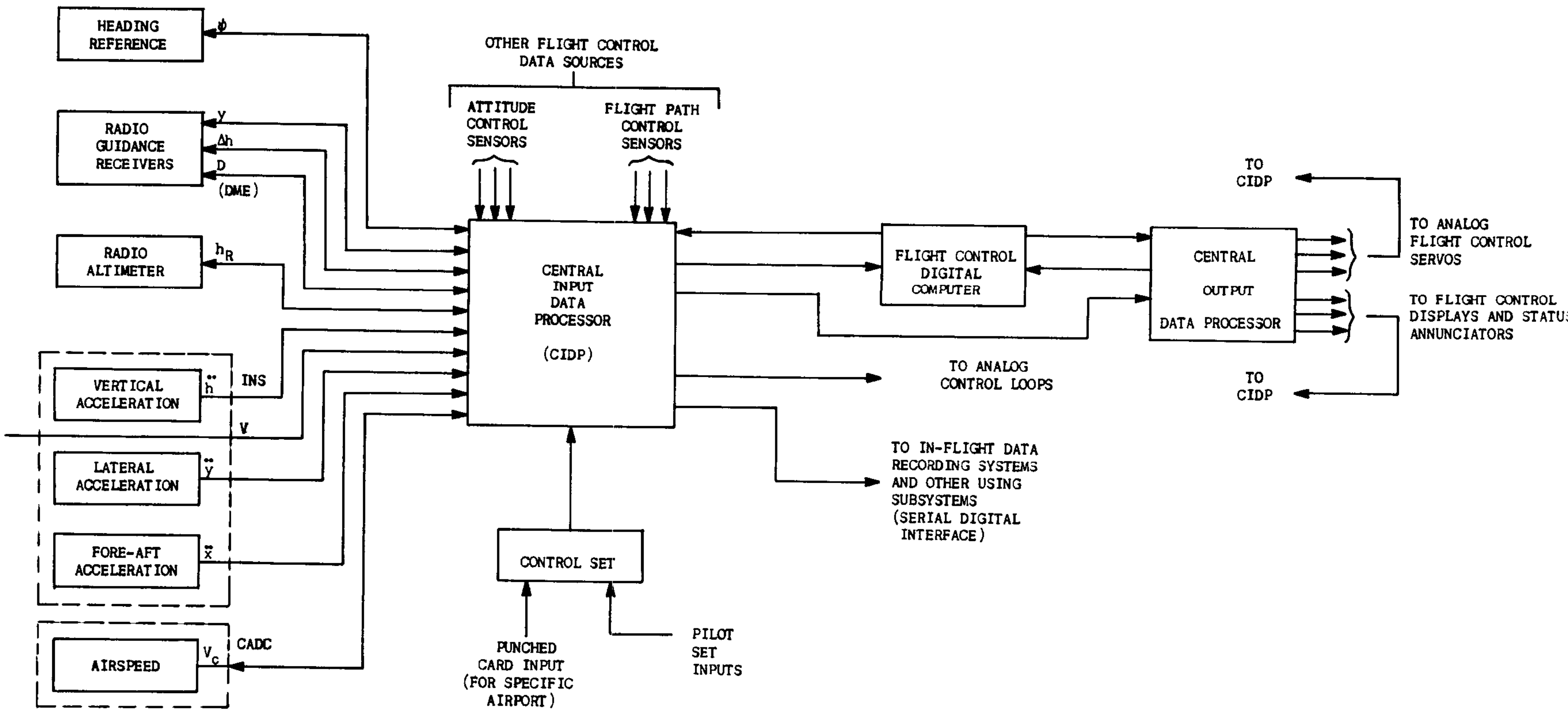
The concepts of integrated digital avionics will be described with reference to a specific systems approach, but most of the principles are sufficiently general to encompass many other variations. The specific approach uses a central digital computer for flight control functions exclusively. Flight control functions include flight path guidance, attitude control, throttle controls, horizontal and vertical situation displays, status annunciators, and associated man-machine interface devices. The functions provided by the digital computer are as follows:

- Flight path guidance law computations (and attitude control if warranted).
- Control mode programming based on pilot selection of specific modes.
- Control mode programming based on the sequential activation of selected procedures and control tasks. These are derived from a stored library of flight plans and operations. They are selected by inserting a preflight or in-flight data card or tape.
- Performance monitoring and testing of interfacing components.
- Electronic display computations - flight director functions, pictorial display perspective laws, alphanumeric annunciator messages, etc.

2. <u>The Central Input Data Processor</u>

The task of an integrated avionics system is to provide the necessary compatibility between the sensing or measurement equipment and the computer on the input side of the problem, and between the computer and the displays and controls on the output side. Figure 9-3 illustrates the all weather landing data flow in such a system. Note that in this block diagram, no demand is made on the input sensors in terms of requiring a standardized digital interface. The sensors can have analog or digital outputs since the problem of compatibility with the computer is solved by the Central Input Data Processor (CIDP). For example, the Inertial Navigation System (INS) will provide a serial-word, serial-bit interface with all other sugsystems if present airline standardization trends continue. This data will also be transmitted at a relatively slow rate (about 300 words per second including identification tag). The Inertial Navigation System data required for the all weather landing functions will have to be processed through a digital-to-digital (D/D) converter before it can be used by the control computer. Thus, having a digital format does not in itself provide compatibility with the digital computer. The digital format is used for INS data because it is the most efficient method of transmitting the information without degrading the accuracy.

Another interfacing sensor is the radio altimeter. Present day units provide dc analog outputs. If the radio altimeter had to provide a digital interface with the computer, it would require its own analog-to-digital (A/D) converter. This is an inefficient method of obtaining such a conversion because



INS = INERTIAL NAVIGATION SYSTEM
CADC = CENTRAL AIR DATA COMPUTER

FIGURE 9-3 ALL WEATHER LANDING DATA FLOW IN AN INTEGRATED DIGITAL AVIONICS SYSTEM multiplexing techniques permit a large number of conversions by a single central A/D converter. Moreover, scattering of data sources in various locations is a poor method of transmitting the data to the computer efficiently. The most effective method of rapidly transmitting large quantities of data to a computer is, in general, the use of a central input source that transmits information in a serial-word, parallel-bit format. Data transfer is controlled directly by the computer and is in synchronism with the computer program.

The Central Input Data Processor (CIDP) is the system component that adapts the various input data sources to the central flight control digital computer. The CIDP would be a special purpose design for each type of aircraft system. As shown in figure 9-3, it receives data from the various AWL sensors as well as other flight control data sources. It processes this data for use by the computer, but it also provides an interface for transmitting information from the computer back to the sensors (self-test commands, for example). The CIDP also provides the data processing function for the man-machine interfaces; that is, the control sets. Included in this category is the possibility of a punched card input for selecing a specific automated landing program associated with a given airport. The control set, in this case, would include the card reader and line driver electronics, but the CIDP would assemble the instruction words for transfer to the computer and would include some of the data checking and verification electronics.

A simplified block diagram of some of the functions performed in the CIDP is shown in figure 9-4. The functions include signal conditioning for the ac and dc analog inputs prior to transmission to the A/D converter's input multiplexer. The A/D converter output is a storage register that transmits a parallel bit word to the computer through dump gates that are enabled by the input control unit. When a data word has been encoded by the A/D converter, the input control unit transmits an input request discrete to the computer. At the proper time within the computer's sequence of operations, it will read the word and transmit an input acknowledge discrete to the CIDP control unit. This initiates transfer of the A/D encoding to the next data word, with the control unit activating the appropriate switching circuits at the multiplexer. The A/D encoding is asynchronous with the computer; but encoding time is considerably shorter than the computer's input data word sampling time. For example, a typical A/D encoding time may be less than 10 microseconds while the computer may sample data words at 1.0-millisecond intervals.

As shown in figure 9-4, other information in addition to the analog signals must be encoded into the proper computer input data format. Serial digital data of the type transmitted by the Inertial Navigation System is decoded in a serial data receiver unit. This unit extracts those words of interest from the serial-word, serial-bit pulse train and stores each word in a separate register. Note that the updating of these registers is asynchronous with both the CIDP and

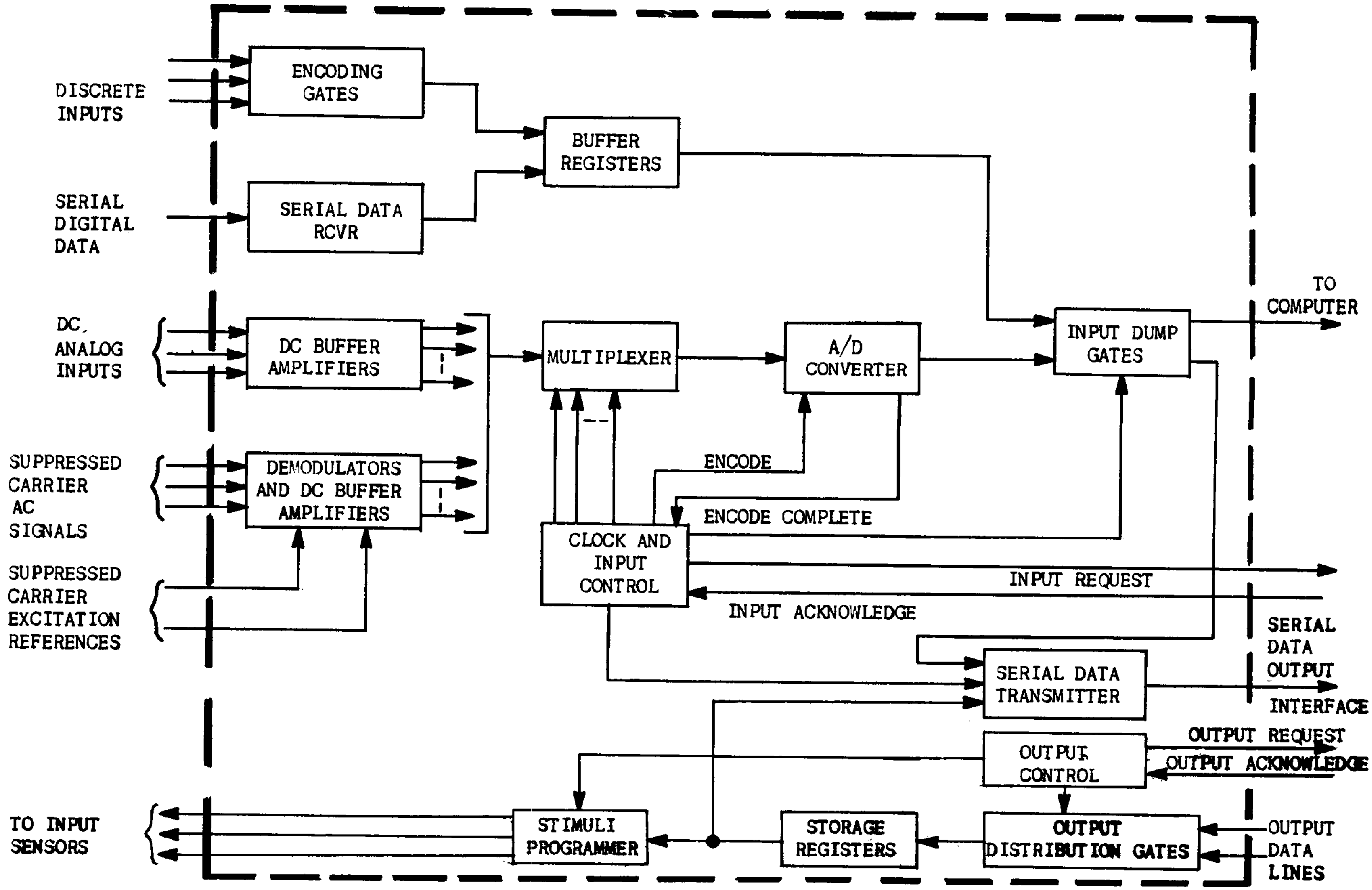


FIGURE 9-4 SIMPLIFIED BLOCK DIAGRAM OF CENTRAL INPUT DATA PROCESSOR

the digital computer. Also, various discrete inputs are encoded into parallel bit words and stored in one or more separate registers. The CIDP control unit will transfer this data to the computer in the same manner that data from the A/D converter registers are transferred. A separate computer input channel may be used. In this case, additional input requests to the computer would be transmitted for these words. However, figure 9-4 shows this group of registers using the same data transfer channel as used by the A/D converter register. The input control unit steers the appropriate register parallel outputs through the input dump gates.

Another function of the CIDP is to encode flight control system data into a serial-word, serial-bit format for use by other subsystems. This is accomplished in the serial-data transmitter block shown in figure 9-4. It transmits words obtained from both the A/D converter and from the digital computer. Because of the asynchronous operation of the A/D converter and the digital computer, the problem of encoding the data into synchronous serial data involves some compromises. A new word appears in the A/D registers at a rate determined by the digital computer's input data sampling rate. This rate is a function of the overall real-time operating program and is not necessarily a fixed rate. If the computer reads input words at 1.0 millisecond intervals, then a complete serial data word (usually 32 bit positions including identity tag, validity bits, parity bit, control bit, and blank period) should utilize less than 1.0 millisecond. That is, the clock rate should be greater than 32 KHz. However, the clock rate should not be much greater than this value because excessive waiting for data can result in a loss of data transmission efficiency. The lack of synchronism between the serial data pulse train and the availability of data to be encoded and transmitted requires that some of the 32 bit position serial data words remain blank occasionally. Since each serial word contains its own identity tag, there is no requirement that these words maintain a fixed position with respect to each other. Hence, the occasional omission of a specific word should not cause any problems.

Another function provided by the CIDP, as shown in figure 9-4, is to provide the means of communicating instructions from the computer back to the sensors. For example, test commands to input sensors may be initiated by means of instructions from the computer; but if the test stimuli are analog voltages, then the necessary signal generation is accomplished within the CIDP. Also, a computer output data line must be used for this purpose. The output request and output acknowledge exchanges of discretes with the computer are similar to those of the input data interface.

3. The Central Output Data Processor (CODP)

This function is included in figure 9-3 as a separate item, although it may be combined with the CIDP. Its primary purpose is to interface the flight control digital computer with the analog parts of the electronic flight controls, with actuation systems, and with the analog and digital flight control displays. The main functions provided are D/A and D/D conversions, as shown in figure 9-5. Three groups of D/A converters are shown in this figure. One group obtains its input from a serial data receiver which accepts digital data directly from another subsystem. That is, this information is not obtained from the flight control computer so that there is no need to decode it in the CIDP. Serial-word, parallel-bit data is obtained from the flight control computer and converted in two groups. A high accuracy group uses separate registers and D/A converters for each word. A low accuracy group uses a single register and D/A converter, but multiplexes the data and sequentially transmits each analog signal to separate sample hold circuits. The D/D conversions include such functions as binary to BCD encoding and electronic circuitry needed to drive digital readouts.

4. Self-Test Loops

Figure 9-3 shows analog signals from the central output data processor being fed back to the CIDP. This is part of a self-test loop. Such continuous self-tests can be implemented in several ways. One method encodes a fixed voltage dummy signal in the CIDP's A/D converter; transmits this signal to the digital computer; compares the value in the computer with the expected value; if valid, transmits it to the output where is is reconverted to an analog voltage and fed back to the input where it is compared with the original dummy analog voltage. Other self-test loops can also be employed to ensure the validity of different data processing functions. For example, in a test mode configuration, the serial data receivers in figures 9-4 or 9-5 may be connected to the serial data transmitter in figure 9-4. A word is transmitted to the receiver where it may be shifted out serially and compared bit-by-bit with the originally transmitted word. This type of check may be made periodically while the system is operating.

5. Alternate Data Interface Concepts

The configurations described above are based on the use of central data processing units that permit the sensor and output devices to have nonstandardized analog or digital formats. There have been trends toward the use of standardized serial digital interfaces for all subsystems and major components in recent military avionics systems. If such a philosophy is applied to the AWL flight control problem, the electronic complexity can become unreasonable. This is illustrated in figure 9-6 where the various sensing, or control process functions F_1, F_2 - - -, represent inputs to the AWL flight control computer. A

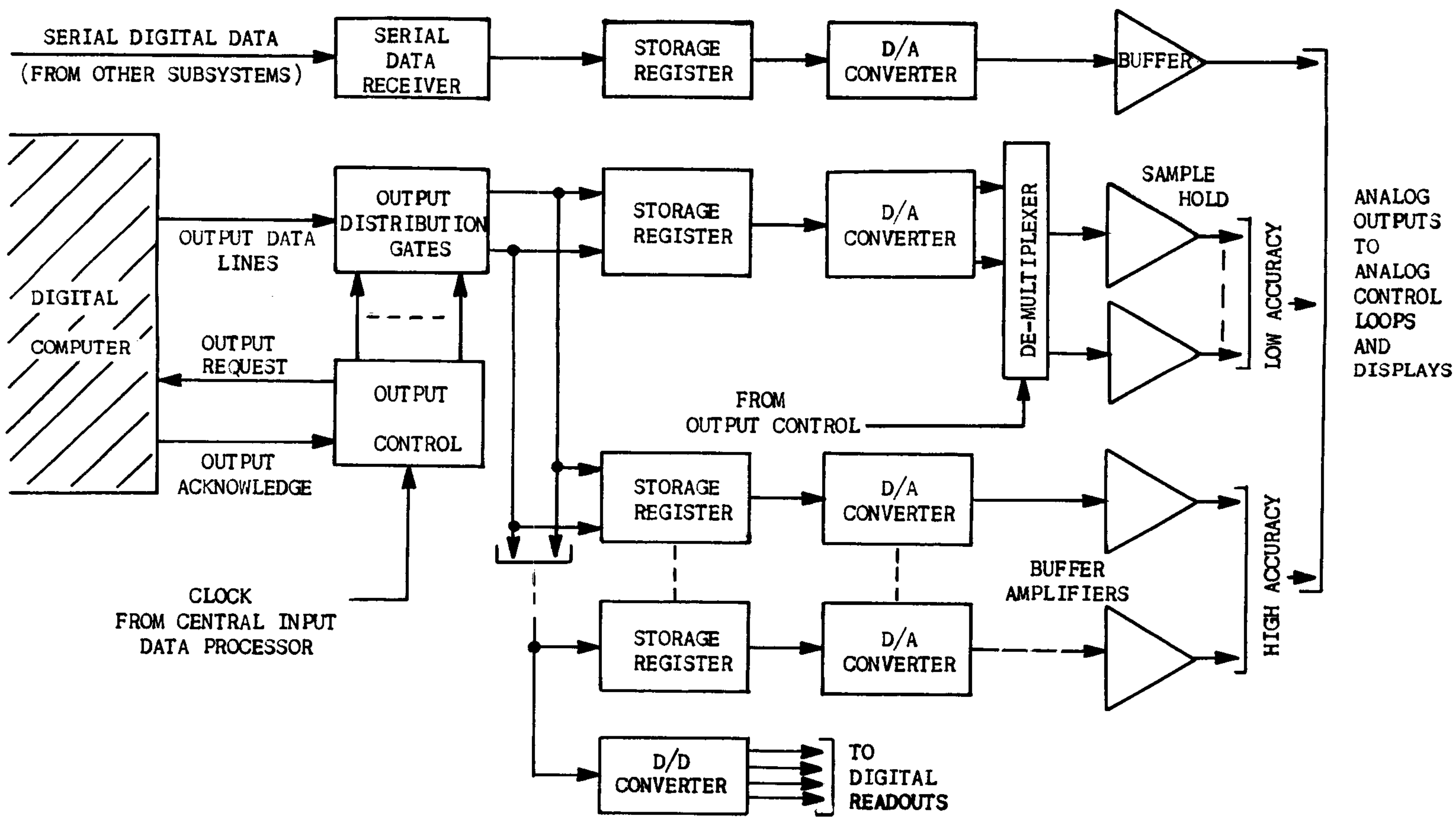


FIGURE 9-5 SIMPLIFIED BLOCK DIAGRAM OF CENTRAL OUTPUT DATA PROCESSOR

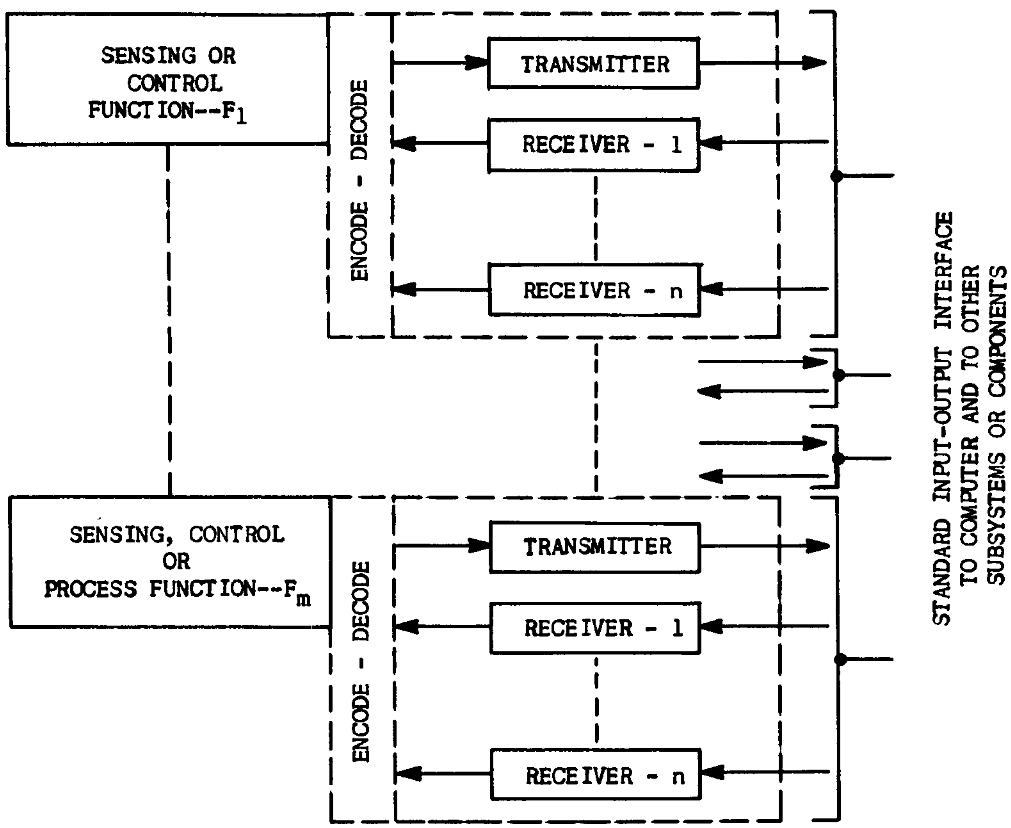


FIGURE 9-6 THE POTENTIAL COMPLEXITY OF A UNIVERSALLY APPLIED STANDARD DIGITAL INTERFACE IN AVIONICS SYSTEMS

standardized digital interface would necessitate one digital transmitter and more than one receiver for each of these components. Over 100 standard digital microcircuits are needed to implement a transmitter and receiver pair. It is apparent that this type of complexity is not warranted if a central processing unit can use common equipment to handle a group of components.

6. Serial-Data Transmission

Although data transfer to the digital computer is in a parallel bit format (but the words are series; that is, transmitted sequentially rather than simultaneously), the digital interface between systems and subsystems, when it exists, is in a serial bit format. A main reason for this approach is the great saving in the number of interconnecting wires. The key electronic components associated with serial digital data transmission are the transmitters and receivers. A typical format contains 32 bit positions in the serial pulse train with allocations as follows:

Bit 1	Control
Bit 2	Validity
Bits 3 to 11	Identification tag
Bits 12 to 21	10-bit data word (bit 12 is least significant bit)
Bit 22	Sign bit
Bit 23	Parity
Bits 24 to 32	Blank

Figure 9-7 shows a timing diagram for one word. Note that part of the identification code is a channel identification. This is a provision for redundant channel operation where data derived from all three of a redundant set of radio altimeters, for example, are transmitted separately on the same line. A block diagram of a serial data transmitter is shown in figure 9-8. A transmitter consists of a 22-bit serial shift register, parallel input dump gates, and a parity generator. The dump gates are used to enter the identification tag and data into the shift register. During the transmission of a word, the 22 bits are shifted out into the data line (control bit first). Each digital "1" shifted out is counted by the parity generator. The twenty-third shift pulse enables the parity generator output which places either a "1" or a "0" on the output such that the total number "1's" will be odd.

The data is shifted back into the shift register, delayed by one shift pulse as it is shifted out. Thus, at the end of any word transmission, the transmitted word is still present in the register, but displaced by one bit

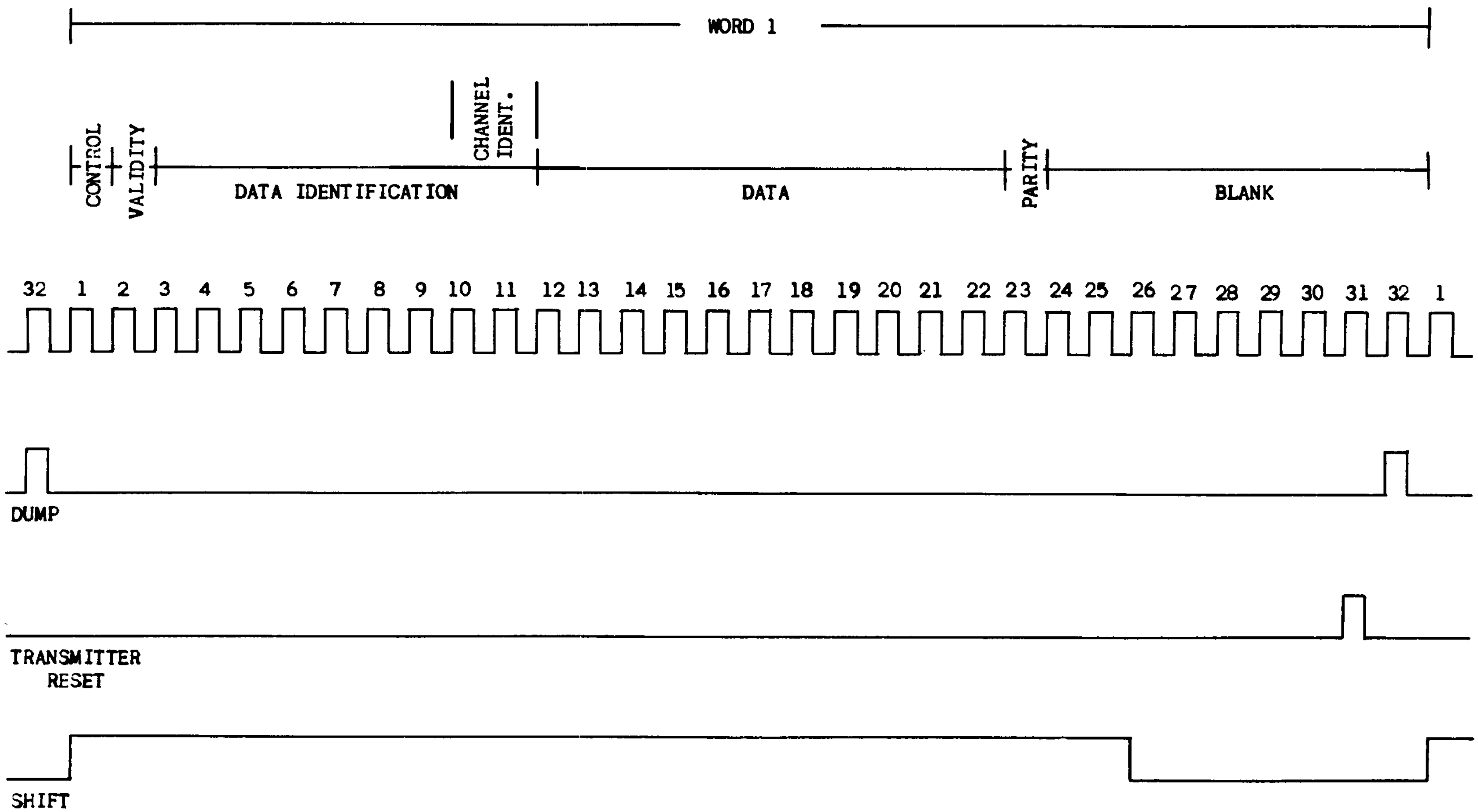


FIGURE 9-7
SERIAL DATA TIMING DIAGRAM

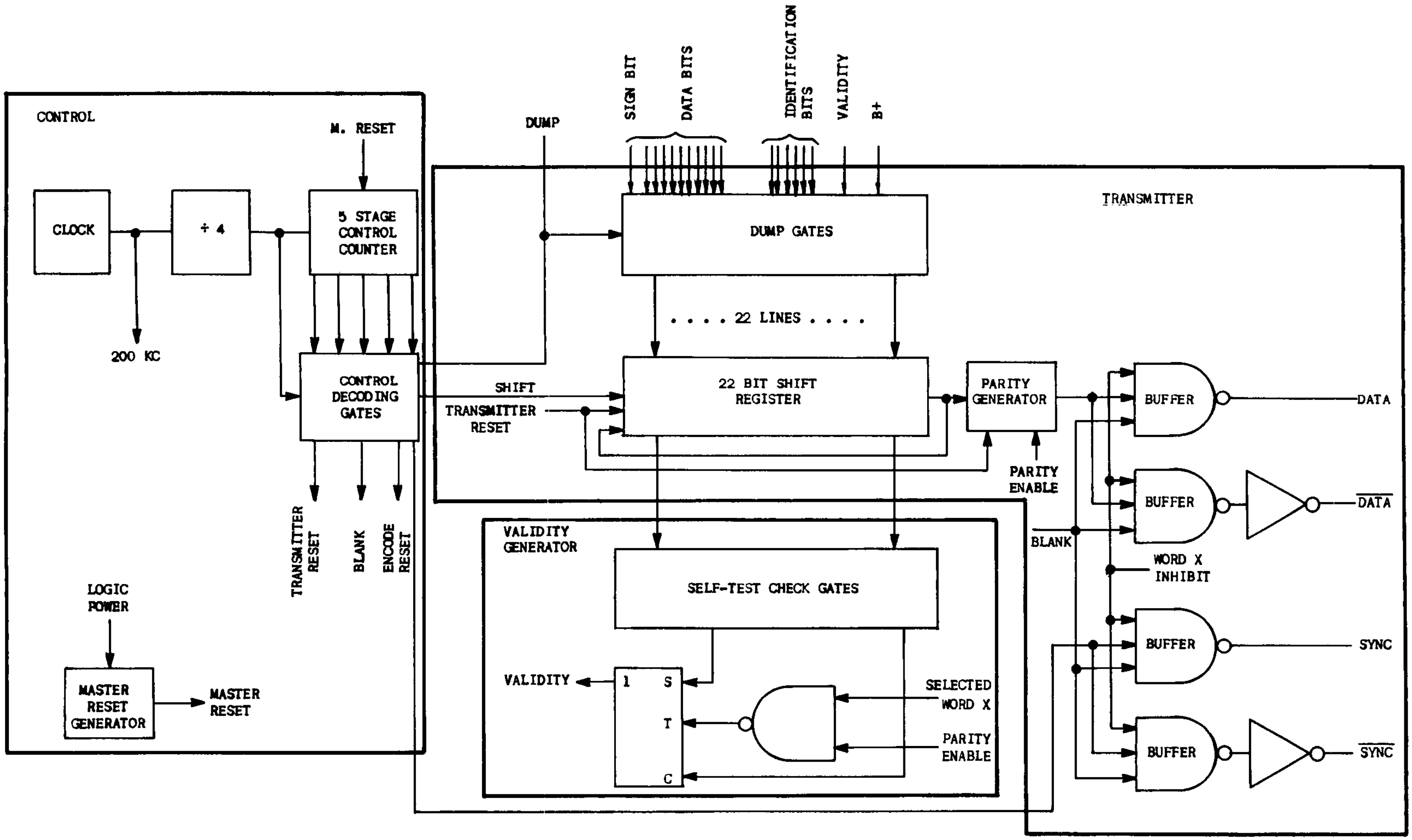


FIGURE 9-8
SERIAL DATA TRANSMITTER BLOCK DIAGRAM

position. This nondestructive readout is utilized in the self-testing and validity checking. The checking may be done with the dummy word (designated word X) that is encoded as a test word by the multiplexed A/D converter. This test word is not placed on the data channel, but could be for checking receivers if desired.

A simplified block diagram of a digital data receiver is shown in figure 9-9. It consits of two input buffer amplifiers, a 23-bit shift register capable of serial input and parallel output, a synchronizing control, a parity generator, good data check, and control gates and buffer storage registers. A receiver is, in general, needed for each serial data transmitter. Also, a buffer register is needed for each word that a receiver is coded to accept. The transfer of data to a buffer register is enabled when the following conditions are met:

- The control bit "1" reaches the last position of the shift register.
- The parity generaotr simultaneously produces a "1".
- The comparison of the identification word with a prewired code indicates that a desired word has been received.

It is apparent from the complexity of this device that an integrated digital avionics system should have a minimum of separate transmitters. A single transmitter or at least a single synchronous data line would have advantages in reducing the number of receivers, but problems associated with central synchronization equipment and the vulnerability to data "hang-up" usually precludes its use in a complex system.

Noise is a traditional source of difficulty in digital data transmission. Corruption of data by coupled signals from other circuits, power supply transients, etc, should be avoided; but adequate protection must be provided if these problems should occur. For example, the transmission (by means of fairly high powered line drives) of the data and its complement is one method of minimizing noise problems. The data is received by differential amplifiers that provide common mode rejection of noise pickup (see figure 9-9). Opening of either input will still allow correct data to be received although the noise margin will be reduced. Relatively low speed data trains and the trend toward higher voltage interfaces also help minimize noise errors. Finally, parity checking eliminates at least half of the noise errors that may occur in transmission. In very critical applications, validity checks can be made on the received data using such criteria as the incremental change in the data word. This requires considerable circuitry and should be avoided to minimize cost and complexity.

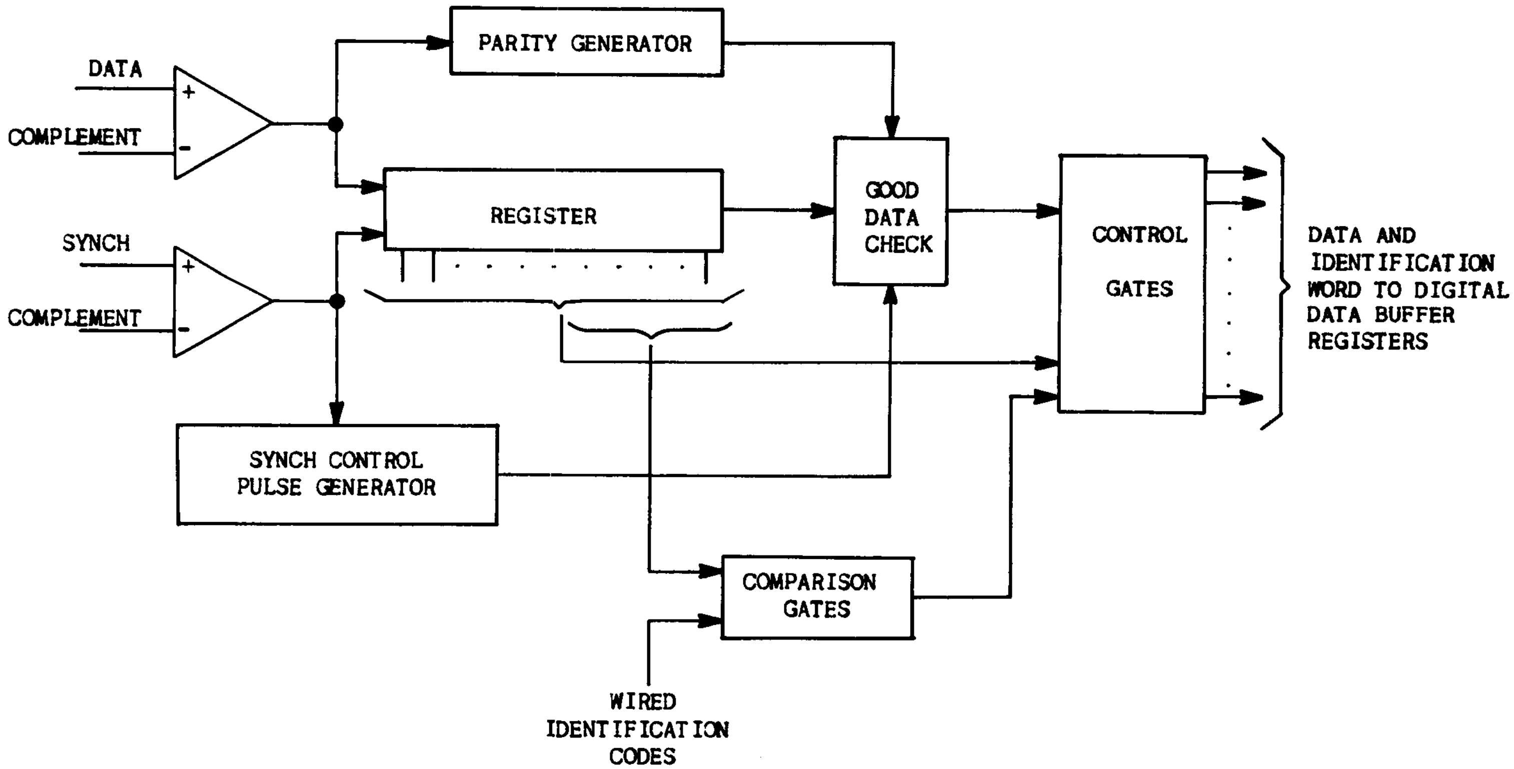


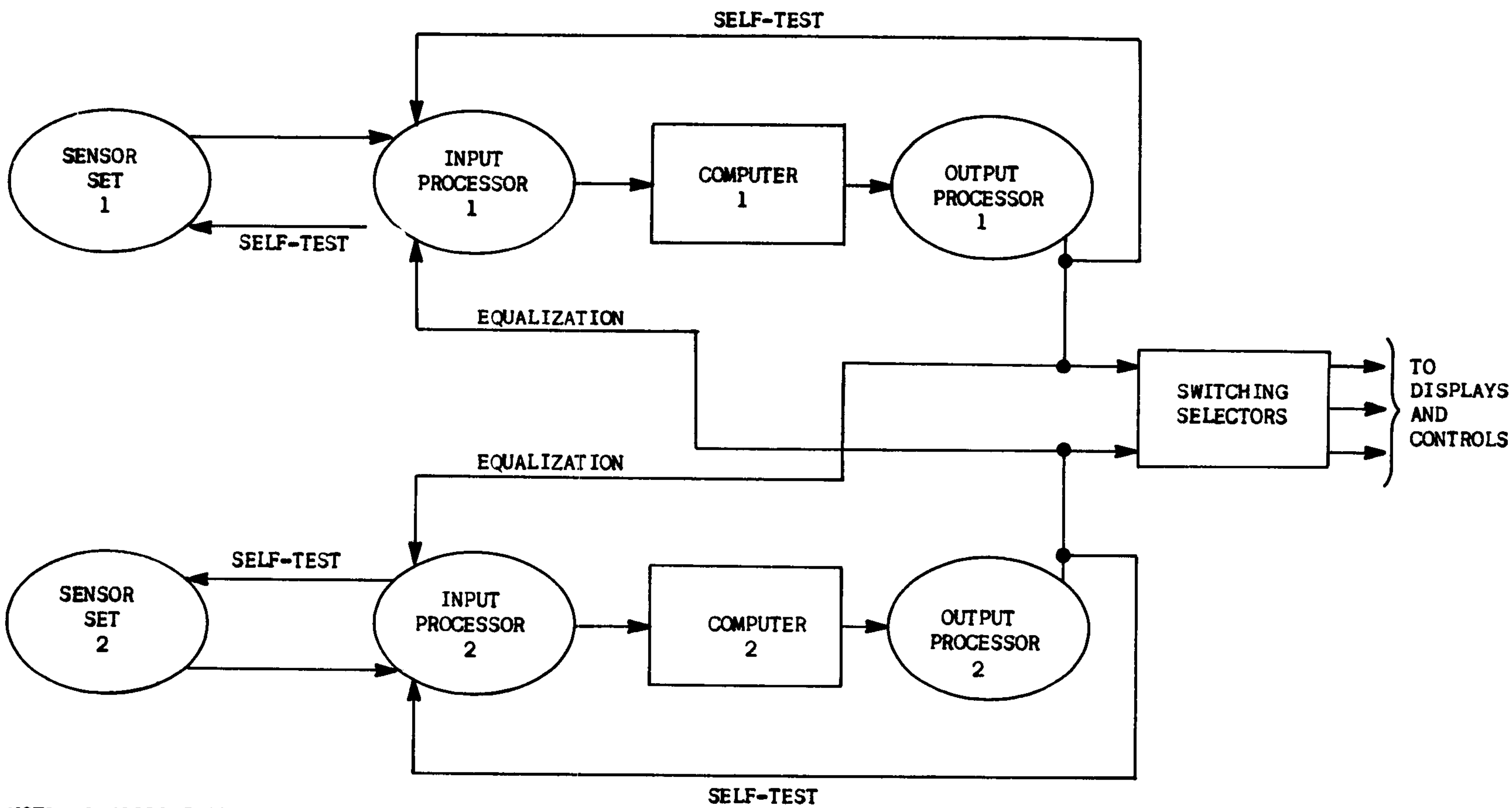
FIGURE 9-9
DIGITAL DATA RECEIVER

7. Computer Organization and Redundancy

Since the digital autopilot must have fail-operational capability for all weather landing, a redundant computer configuration is mandatory. Moreover, the sensor input data and the central data processors must be redundant. There are many possible configurations for combining these redundant elements to obtain a fail-operational system capability. These possibilities, however, are primarily conceptual for, as far as can be determined, no truly fail-operational, digital autopilot systems have been built. Concepts can be examined for philosophical advantages and disadvantages and for compatibility with reliability objectives in a gross sense. Only when a system is committed to the detailed design effort required to implement the concepts are the real problem areas properly exposed to an engineering evaluation. As pointed out in the prior section on Reliability and Redundancy (Section VI), there are certain empirical principles that contradict the quantitative theories when redundant configurations are under consideration. When dealing with redundant analog channels, the empirical principle was to minimize interactions or connections between different channels. In the case of digital systems, the tendency to cross-connect data between computers, sensors, and input-output processors is apparent in many preliminary studies of redundant digital autopilot configurations. Whether this practice can lead to unanticipated complexity problems remains to be determined in the detailed engineering design studies.

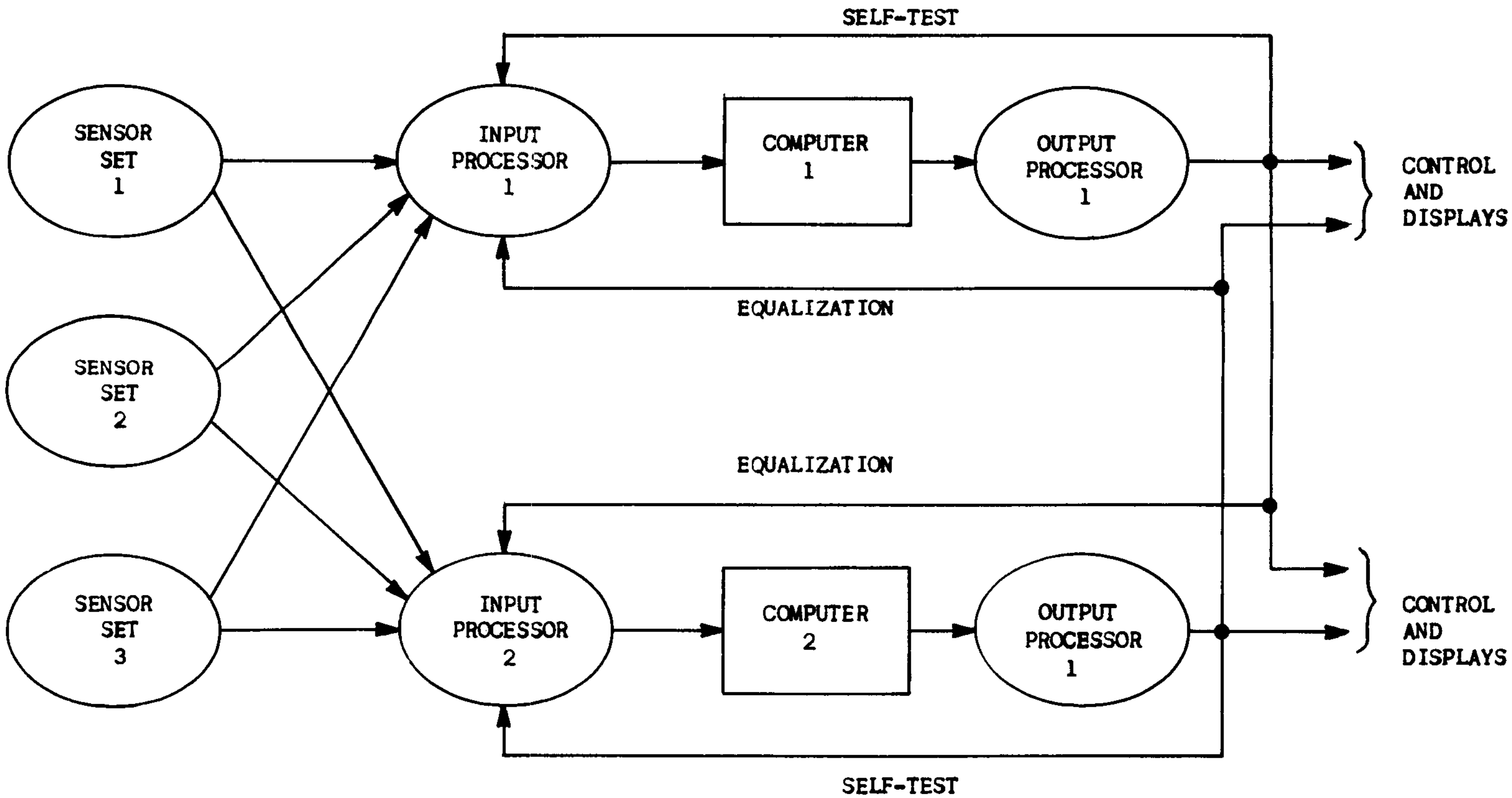
Some of the general factors regarding the choice of a best approach can be illustrated with reference to the conceptual redundancy diagrams shown in figures 9-10a, b, and c. The simplest configuration is the dual, noninterconnected (except for long-term equalization) combination of sensors, processors, and computers (figure 9-10a). Its ability to provide a fail-operational capability is based on the assumption that any failure within any element of a channel is internally detectable. This self-test capability may be rationalized for the digital computer and the input-output data processors; but the validity of such an assumption is questionable for the sensors. For example, if one radio altimeter reads 18.29 meters (60 feet) and the other reads 16.46 meters (54 feet), and self-test circuits indicate that outputs of both units are valid, which altimeter should initiate the flareout maneuver? The ability of sensor self-test functions to detect small bias errors of this type is doubtful in the present state of the art. Hence, we are compelled to add the third sensor and use averaging or mid-value voting techniques.

One version of system growth to include triplex sensors is shown in figure 9-10b. A configuration employing full triplex sensors, processors, and computers is shown in figure 9-10c. This latter configuration is representative



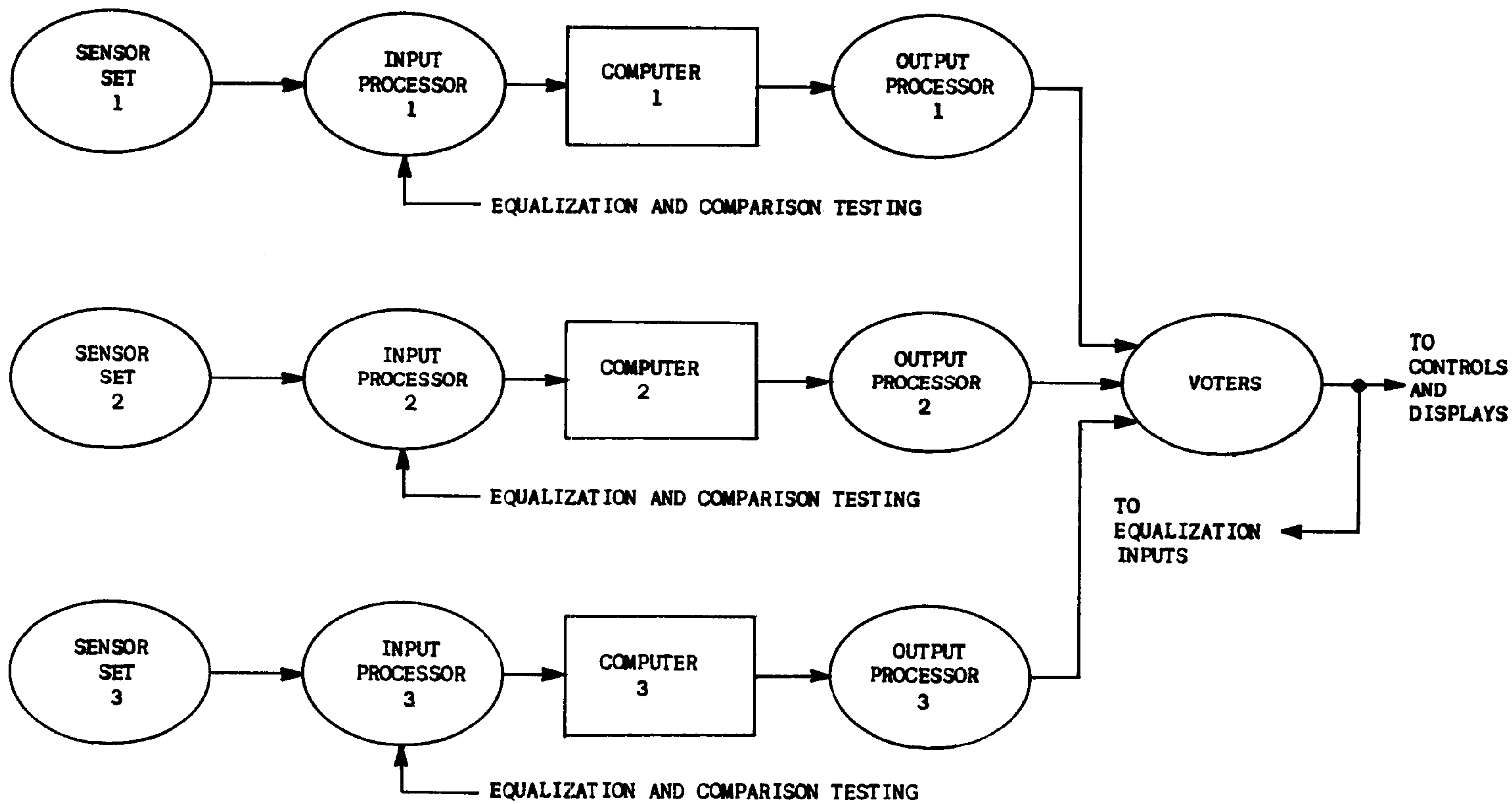
NOTE: SENSORS INCLUDE CONTROL SETS

FIGURE 9-10a
CONCEPTUAL REDUNDANCY DIAGRAM
DUAL CONFIGURATION WITH CONTINUOUS SELF-TEST (Channel 2 Standby)



NOTE: SENSORS INCLUDE CONTROL SETS

FIGURE 9-10b
CONCEPTUAL REDUNDANCY DIAGRAM
DUAL COMPUTER - TRIPLEX SENSOR CONFIGURATION (Channels 1 and 2 both active)



NOTE: SENSORS INCLUDE CONTROL SETS

FIGURE 9-10c
CONCEPTUAL REDUNDANCY DIAGRAM
TRIPLEX SENSOR - COMPUTER WITH OUTPUT VOTING

of present state-of-the-art techniques for fail-operational analog autopilots. There is no doubt that figures 9-10a and 9-10b represent more effective methods of achieving fail-operational capability than the full triplex system. The key question is whether the computers and their interfacing electronics can detect their own failures by means of their continuous self-checking routines. Obviously they can detect some failures, but the important considerations are as follows:

- How close to 100 percent effective are the self-checking routines?
- How much programming time and/or equipment complexity is needed to approach 100 percent self-checking effectiveness?

The significance of these questions can be demonstrated by a quantitative example taken from a recent Sperry Phoenix Company study on computer redundancy configurations. The objective was to obtain a mission failure rate of no more than 1.7×10^{-8} for the autopilot during the last 4 minutes of the approach and landing. The dual self-checking system (similar to figure 9-10b) was evaluated in terms of computer and interface reliability and self-checking effectiveness. The mission reliability, R_M, for the system is given by

$$R_M = 1 - (P_c \lambda t)^2 - 2(1 - P_c)\lambda t$$

where

P_c = Probability that a failure will be detected by self-check

λ = Single channel failure rate

t = Mission time (4 minutes)

Figure 9-11 is a plot of mission reliability versus computer (and interface electronics) MTBF for various values of self-check efficiency. For example, if we assume an MTBF of 6000 hours for the computer, then the self-check must detect all failures with a probability of 0.9995.

An MTBF of 6000 hours for the computer and processor electronics is probably beyond the present day state of the art. Likewise, self-checking (performance within milliseconds) with a 99.95-percent effectiveness is probably beyond the capability of present day computers. Self-check procedures under consideration include memory tests for checking both the fixed and the variable memories and tests for checking the arithmetic unit. The memory sum test is 100-percent effective in detecting single failures in the fixed memory, the read electronics and the cores. The variable memory test detects all failures in the electronics portion of the variable memory, but not the cores. Failure of cores is rare, and the relatively small number of them in the variable memory makes this factor negligible compared to the uncertainty in the arithmetic unit tests.

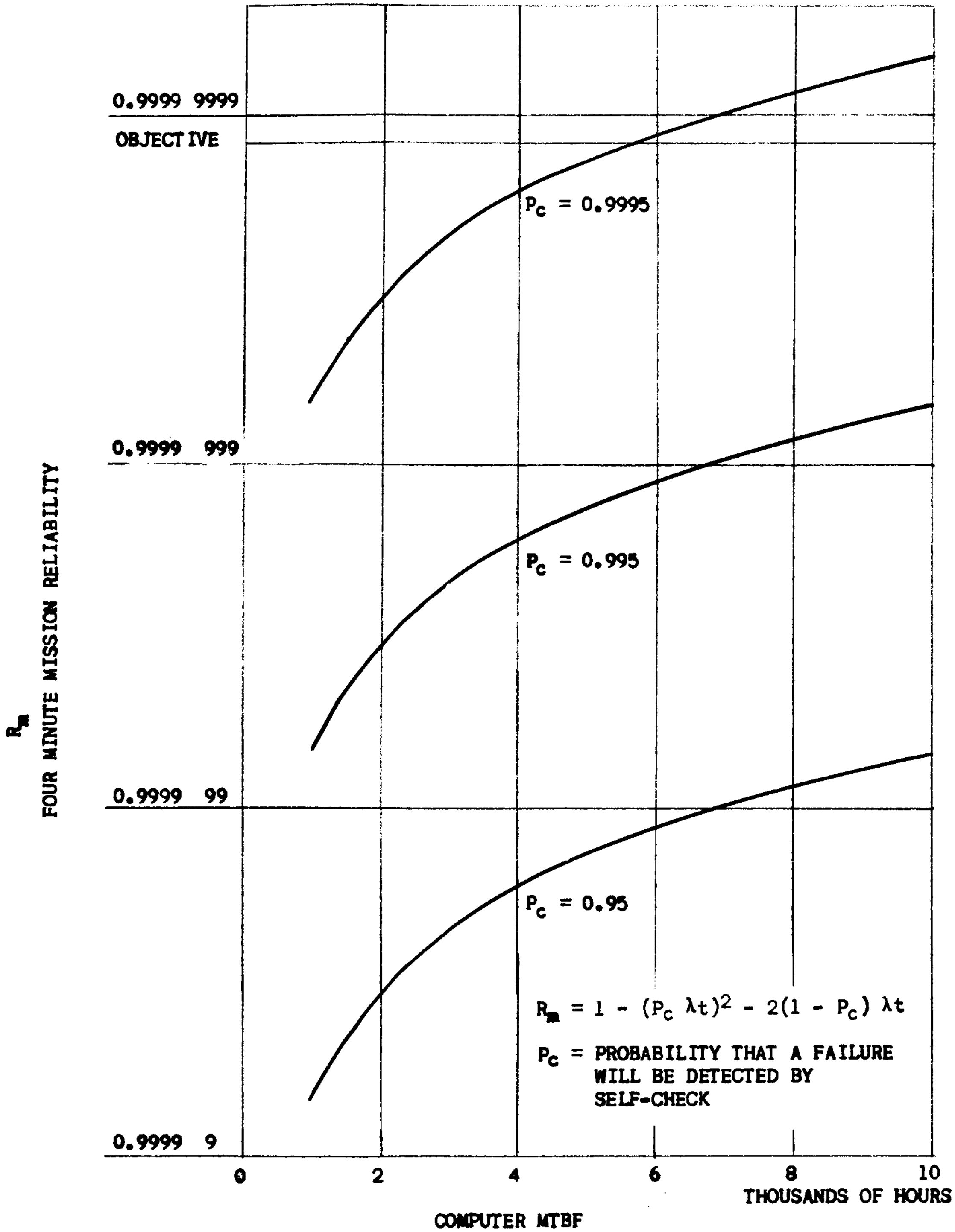


FIGURE 9-11
MISSION RELIABILITY VS COMPUTER MTBF FOR DUAL SELF-CHECKING SYSTEM

The arithmetic and control unit represents a more complex problem. It is estimated that programs can be designed to detect at least 99 percent of failures in this part of the computer. Now, in order to get the probability of detecting a failure up to 0.9995, additional independent techniques are required to detect possible failures.

There are several techniques that may be used to increase the proability of detecting failures. The simplest method is to complete a process of validation of all computed quantities before transmitting them out of the computer. A computed output is checked to ensure that its magnitude, its rate of change, and its acceleration do not exceed expected limits. The magnitude limit is most easily achieved by scaling so that the largest computer number is equal to the maximum value of the variable. Thus, no computer time is needed for magnitude limiting. The rate limit is achieved by ensuring that the change in a parameter from one computation cycle to the next does not exceed the expected value. The acceleration of a computed quantity is determined by taking the difference between the quantity and the value predicted for it by means of a simple linear extrapolation. This is checked against a known limit before validating the data.

It is apparent that the imposition of an extremely stringent failure probability such as 1.7×10^{-8} in 4 minutes is pressing even the extrapolated state of the art of avionics equipment. Moreover, it should be noted that the practices employed in certifying automatic equipment for all weather landing operations have not recognized MTBF as a criterion of reliability. The emphasis has been on safety regardless of predicted reliability. Systems are scrutinized for possible failure modes. If an equipment failure can be postulated (with some reasonableness), then it must be domonstrated that its effect will not compromise safety or performance. Often, considerable equipment may be added to eliminate a failure possibility that can cause safety or performance hazards. Digital systems have not been subject to this type of scrutiny because they have not yet progressed to the point where specific hardware failures can be identified and evaluated. Considerable research and experimental hardware studies relating to this type of problem must be done before the integrated digital avionics system can fulfill its potential in automated all weather landing operations.

D. SUMMARY AND CONCLUSIONS

1. Present day automatic flight control systems used for all weather landing operations employ analog guidance and control computations that are programmed by internal, special purpose, digital logic elements. These systems are more

effective, from the standpoint of cost, size, and performance, than competitive systems based on general purpose digital computers if the required functions are limited to those being performed by 1967 state-of-the-art systems.

2. The advantage of a digital computer oriented all weather landing system is its ability to provide a level of automation not obtainable with state of the art analog type systems. This type of automation could relieve the pilot of the burden of performing a multitude of sequential procedures in the dial-setting and switch-throwing category now associated with automatic landing operations.

3. A digital all weather landing system appears most reasonable if the digital computer provides the flight control functions for other phase of an SST type aircraft's flight. These functions are as follows:

- Flight path guidance and control and possible attitude stabilization.
- Control-mode programming from pilot select inputs or from data cards or tapes inserted prior to flight or during flight.
- Performance monitoring and testing of interfacing components.
- Electronic display computations.

4. A major equipment item of such a system (in addition to the digital computer) is a central data processing subsystem that adapts the various input data sources to the central digital computer. There are complexity disadvantages to requiring that the input sensors have standard digital interfaces. The central data processor provides the necessary interface compatibility and also encodes and transmits all important flight control data in a standard digital format. This latter transmission is for use by any other airborne subsystem.

5. The main technological problem associated with an integrated digital flight control system involves methods of achieving the necessary reliability and safety for automatic landing. Digital systems have a better self-checking capability than most analog type systems, but the effectivenesss of the self-check in a short time interval must be higher than present day digital computers can provide if this capability is to be used successfully. Considerable study is required on the engineering problems associated with fail-operational digital systems before acceptable redundant configurations can be defined.

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