Development of the F-12 Aircraft Flight Control System

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This paper presents a description of the manual and automatic flight control system of the F-12 series aircraft, the first supersonic cruise vehicles. The impact of the aircraft configuration and flight regime on the design philosophy is reviewed and the development process from initial analog computer analysis to first flight is described. Flight experience including reliability of the triple-redundant, fail-operational stability augmentation is presented. Differences from conventional flight control practice are noted and justified. The inadequacy of certain conventional pilot presentations is discussed. Finally, the control problems encountered in high-speed, high-altitude flight are identified and treated.

Introduction

THE requirements and design criteria of a flight control system are, of course, dictated by the vehicle's mission and configuration. The F-12 series aircraft are designed for sustained cruise at high supersonic Mach numbers. Efficient supersonic cruise dictates low drag and minimum weight.

Designed more than ten years ago, the F-12 series aircraft was the forerunner of two presently popular design concepts, the blended body and the control configured vehicle (CCV). The objective of both concepts is to increase aircraft performance. The blended body improves performance in several ways: area ruling reduces supersonic wave drag, forebody shape can induce vortex lift on the wing and can also carry a significant percentage of the total lift on the forebody, and the forebody lift also moves the aircraft center of pressure forward and thereby reduces trim drag. Control configured vehicles utilize the principle of active controls to permit flight in unstable flight regimes to reduce trim drag, to decrease control surface size to reduce friction drag and weight, and to suppress flutter modes to reduce weight by reducing structural stiffness requirements. The application of these concepts to the F-12 series aircraft had considerable impact on the flight control system.

Configuration

The configuration is illustrated in Fig. 1. The wing is a delta planform with an approximate 60° leading edge sweep. The theoretical wing area is approximately 1800 ft^2. The wing is mounted with a negative incidence relative to the fuselage. The two engine nacelles for the Pratt & Whitney J-58 engine are located at approximately mid-semispan. An all-movable vertical tail is mounted on the top aft portion of each nacelle. The fuselage is long and slender with chines forming a relatively flat bottom. Overall fuselage length is 100+ ft. The interceptor version of the F-12 series aircraft does not have the chines extending completely to the nose and is equipped with a large radome. This nose modification requires the addition of a large centerline folding ventral and small nacelle ventrals to provide equivalent directional stability at high Mach numbers.

The fuselage and chines carry a significant percentage of the total lift and move the center of pressure forward at supersonic speeds which, in combination with center-of-gravity control through the automatic fuel control system, permits the aircraft to operate at low, neutral, or negative levels of pitch stability. This reduces supersonic trim drag. Flexibility of the long forebody adds significantly to this effect reducing pitch stability by 4–5% at high Mach numbers and 7–8% at transonic Mach numbers at maximum design dynamic pressure. The chines also reduce the directional instability contribution of the fuselage and the required vertical tail size. The vertical tails are canted inboard 15° to minimize the rolling moment due to sideslip or vertical deflection. The nacelle location, although near optimum relative to minimal flow field distortion at the inlet, results in a severe yawing condition upon engine failure or inlet unstart.

In addition to configuration effects, the F-12 series aircraft cruise altitudes have a significant effect on aerodynamic damping of the short period pitch mode and the lateral directional Dutch roll mode. Aerodynamic damping is almost directly proportional to the square root of the density ratio. Thus, the damping ratio can be expected to be 19% of the sea level value at 80,000 ft. This percentage is reduced further because of the normal reduction of the aerodynamic derivatives with increasing supersonic Mach number.

The design criteria established for the flight control system of the F-12 series aircraft was that the system must be simple and highly reliable. Simplicity dictated a relatively conventional system, but reliability dictated sufficient redundancy in axes affecting flight safety to yield a fail-operational system. In addition, the primary flight regimes had to be optimized to meet the then existing measures of good handling qualities for the short-period pitch mode and the lateral directional Dutch roll mode. Residual motions in supersonic cruise were also to be limited to the Military Specification requirements of ±5 mils of attitude deviation applicable to the stable platform requirements of bombers, fighters, or reconnaissance aircraft.

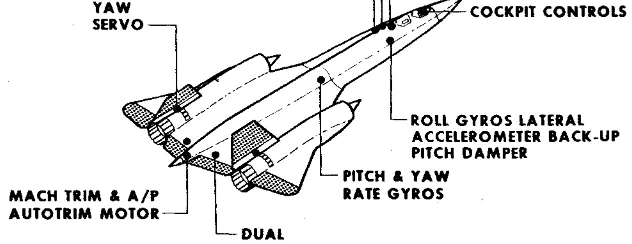

Fig. 1 F-12 series aircraft configuration and control system component locations.

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An adaptive flight control system was considered for the F-12 series aircraft, since considerable work was being done on these systems in the early 1960's. No actual applications had been made, however, and the development risk in combination with the fact that most adaptive systems at that time required continual disturbance of the aircraft for determination of the instantaneous required gain was inconsistent with the development schedule and the stable platform requirements of the vehicle.

It is interesting that the F-12 series aircraft's flight control system represented a rudimentary form of fly-by-wire since the vast majority of flight time is on autopilot. The notable exceptions are during takeoff, landing, and refueling. Even on the manual flight control system, the aircraft response is grossly modified by the highly reliable stability augmentation system. The amount of flight time that has been spent without the assistance of the stability augmentation system or autopilot involving loss of any one of the three axes, yaw, pitch, or roll, is conservatively estimated at under ½% total. Loss of the stability augmentation system and autopilot in all three axes is measured, at most, in seconds and has been due to power transients.

Manual Control System

The shaded areas in Fig. 1 indicate the movable surfaces used for control of the aircraft. Note that only elevons and all-movable verticals are utilized. The inboard and outboard elevons are utilized for pitch and roll control. Pilot control stick motion is separated into pitch and roll commands by the elevon mixer assembly located in the aircraft's tail cone. The outboard elevon is rigged 3° trailing edge up relative to the inboard elevon. This in combination with approximately 5° of conical camber of the outboard wing leading edge reduces wing root bending moment under critical flight conditions. The outboard elevon is slaved to the inboard elevon through a torque tube system which transmits commands across the hot aft nacelle. The outboard elevon provides approximately 85% of the roll control power whereas the inboard and outboard elevons have approximately the same effectiveness in pitch control.

Pitch control is limited to 24° trailing edge up and 11° trailing edge down. This provides good pitch control throughout the flight envelope and positive nosewheel liftoff during takeoff at all flight loadings.

Roll control is limited to ±24° included angle below 0.5 Mach number and ±14° above 0.5 Mach number. This provides excellent roll control in landing and takeoff and throughout the flight envelope while avoiding roll coupling problems at higher Mach numbers.

The all-movable vertical tails provide the necessary control power for an engine failure on takeoff or at cruise Mach number and excellent crosswind landing capability. Comparable to the roll control, the all-movable verticals are limited to ±20° below 0.5 Mach and ±10° above 0.5 Mach.

Trim capability is provided in all three axes. In pitch and roll, series trim is utilized and therefore trim deflections are not reflected in control stick position. Parallel trim is used in yaw and thus the trim deflection is reflected in rudder pedal position. The two primary requirements for trim on the aircraft are pitch for attitude control and yaw for engine-out conditions. As a result, normal aircraft trim control practice is modified in that the control-stick trim button provides pitch and yaw trim rather than pitch and roll. Roll trim and right-hand rudder trim for surface synchronization control is provided on the left console forward of the throttles. Trim position indicators are provided for all three axes on the center instrument panel. Due to the loss of manual dexterity from use of a pressure suit and the multiplicity of circuit breakers, a trim power switch is located directly ahead of the pilot's left knee. This switch cuts power to all trim systems and is used in the event of a runaway trim failure. Once the runaway condition is stopped, the pilot can pull the proper circuit breakers and re-engage the trim power switch to restore power to the unfailed systems.

Control forces are provided by spring bungees. Breakout forces were minimized by close attention to the design of the cable system and meet the requirements of Military Specifications. Aileron and rudder positions and control forces are essentially linear with stick and pedal position. However, elevon pitch position vs stick position is intentionally a nonlinear mechanization. Cruise flight is at very low levels of pitch stability and the aircraft is very sensitive to elevon inputs. Thus, elevon deflection per unit stick deflection is kept low about the neutral stick position to provide better vernier control. This is important primarily if the pitch stability augmentation system has failed since normally this system has a similar effect by opposing pilot inputs.

The irreversible control system is hydraulically powered by two independent systems. Pilot commands through the control stick or rudder pedals are transmitted to the hydraulic actuators through a dual cable system. No power boost is used between the cockpit and the hydraulic actuators. Tension regulators are utilized to eliminate cable slack over the large temperature range and to account for fuselage deformation during a normal flight. To minimize cable expansion with temperature, the cables are made of Elgiloy, the watch-spring material.

Automatic Flight Control System (AFCS)

The AFCS of the F-12 series aircraft consists of the stability augmentation system (SAS), the autopilot, and the Mach trim system. The SAS was considered an integral part of the aircraft control system and as such required reliability equivalent to the basic flight control system in the critical axes of pitch and yaw. The autopilot was primarily to provide pilot relief modes and although high reliability was desired, an autopilot failure was not considered to affect safety of flight. The Mach trim system was to provide speed stability in the subsonic and low supersonic speed regime and is not critical. However, lack of this function would increase pilot attention and workload in maintaining airspeed.

The pitch and yaw rate gyro packages are located on an antinode of the fuselage bending modes to avoid aeroelastic mode sensing. This location is in a fuel tank requiring a cutout for installation. When the fuel in this tank is depleted the thermal environment exceeds the temperature limits of the gyro. Rather than attempting to develop high-temperature-rate gyros, the problem was circumvented by providing a unique insulation system. The sealed gyro package is encased in a jacket filled with a heat sink of stearic acid. This in turn is enclosed in a layer of insulation which is then surrounded by a jacket through which fuel is circulated for cooling.

The control surface servos and the trim motors are designed for the high-temperature environment. All other components of the AFCS are located in areas serviced by the environmental control system (Fig. 1).

The AFCS was designed to provide optimum handling qualities in the primary flight regimes of the aircraft. Since the vehicle would spend the greater portion of its flight time at high Mach number cruise, the handling qualities had to be optimum at these conditions. In addition, it was imperative to provide good response and controllability in the critical areas of takeoff, landing, and refueling. Figure 2 indicates the flight regions that were emphasized in the AFCS design. All other flight conditions were considered transitional where handling qualities could be less than optimum in the interest of simplicity, and hence reliability of the control system.

Table 1 Manual vs SAS authority

Axis	Manual authority M <0.5	Manual authority M >0.5	SAS authority	Percentage manual authority M <0.5	Percentage manual authority M >0.5
Pitch	−24°, +11°		−2.5°, +6.5°	10, 59	
Roll	±24°	±14°	±4°	17	29
Yaw	±20°	±10°	±8°	40	80

The Honeywell Corp. was subcontracted to provide the AFCS and the air data computer (ADC) to design requirements established by Lockheed. Honeywell designed and built the nation's first triple-redundant, fail-operational SAS for the F-12 series aircraft in the pitch and yaw axes. In the thousands of operational flight hours since the inception of the program, the pitch and yaw SAS has suffered only two system failures. One was a maintenance error, and the other occurred when both the pitch servos failed in the same flight. There were other instances where all three channels were simultaneously disengaged due to power transients during generator failures and subsequent switchover to the remaining generator. However, the channel disengage logic was immediately recycled and the system functioned normally. The one hardware failure during operational usage can be equated to a mean time between failure (MTBF) of approximately 130,000 hr vs a predicted MTBF of 19,000 hr. These numbers are based on total system operating ground and flight hours in an operational environment and exclude Category I and Category II flight testing.

Stability Augmentation System (SAS)

The F-12 was designed with low static stability to minimize trim drag, and it encounters low directional stability at high Mach numbers. In addition, an engine-inlet unstart can produce relatively violent transients during which the pilot can become quite disoriented relative to which inlet has unstarted. Furthermore, at high altitudes, inherent aerodynamic damping is quite low. These characteristics dictate full-time use of the yaw and pitch stability augmentation systems (SAS) to provide damping, pitch, and directional static stability and the proper corrective action during an unstart. These characteristics then implicitly dictate that the SAS contribution to the handling qualities be considered integrally with the free airplane characteristics at all times.

To achieve the objectives established for the SAS, significant percentages of full manual authority were required. The comparative authorities are presented in Table 1.

Pitch SAS

Since a full-time SAS is employed in the aircraft, theoretically the vehicle characteristics could be modified to produce any type of handling quality desired. However, as was stated earlier, a constraint was to maintain simplicity with handling qualities being optimum for the regions shown on Fig. 2 and at least acceptable in the rest of the flight regime. There was a degree of uncertainty in defining handling qualities at Mach 3 flight in that it was felt at those speeds the pilot's respect for the vehicle might have some influence on what he would consider optimum. Taking this into account and combining it with information obtained from Ref. 1, the performance constraint contour of Fig. 3 was developed. This contour was then used as a design goal tempered only by the requirement of maintaining simplicity.

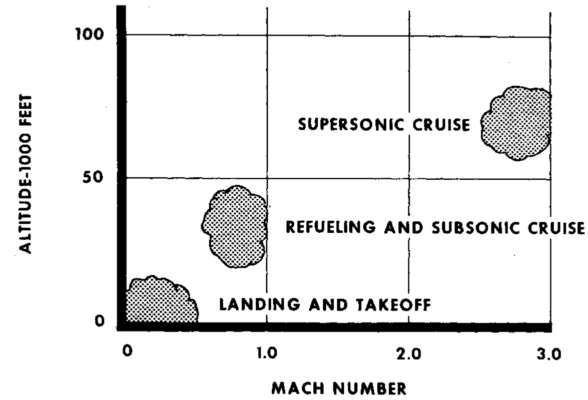

Fig. 2 Design flight areas for F-12 type automatic flight control.

Functionally, the pitch SAS is relatively conventional, utilizing pitch rate scheduled with pitot differential pressure and altitude for both damping and static stability augmentation. For a linear perturbation math model, it can readily be shown that high-passed pitch rate augments damping and lagged pitch rate augments the static stability where the time constant of both the lag and the high pass is the so-called airplane pitch response time constant. Since pitch rate can be decomposed to the sum of high-passed and lagged pitch rate, it can be shown that a straight through system augments both damping and static stability where the damping portion is weighted by the magnitude of the airplane time constant. At high altitudes and Mach number, the airplane time constant for the F-12 series aircraft is relatively large, ranging from 6–10 sec. Thus, with a purely proportional system, the gain required to provide the desired static stability augmentation would result in overdamping. To circumvent this, a lagged pitch rate term with fixed gain and time constant is switched in above 50,000 ft. Although the time constant match is not perfect at all conditions during cruise, it is sufficiently close to achieve the desired results. Furthermore, the large value of the mechanized time constant (6.5 sec) minimizes the transient that occurs if the term is switched in during a pitch rate maneuver.

Yaw SAS

The directional stability of the F-12 series aircraft is always positive, but at high Mach numbers its value becomes quite low. This, coupled with some potentially violent yaw transients induced by engine-inlet unstarts, creates the need for directional stability augmentation. This results in a fairly conventional yaw SAS including high-passed yaw rate scheduled with pitot differential

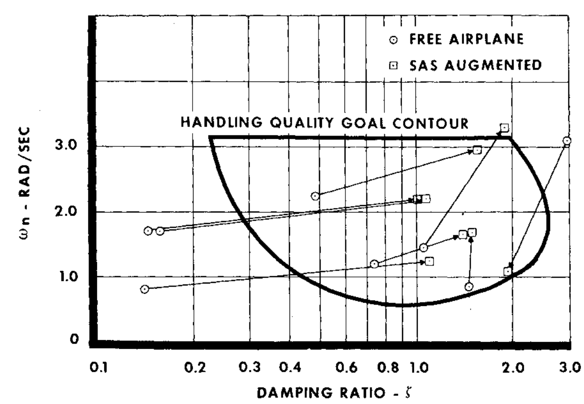

Fig. 3 Typical pitch short period characteristics.

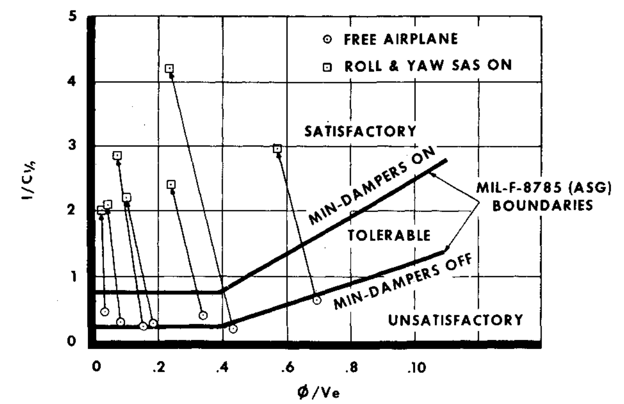

Fig. 4 Typical Dutch roll characteristics.

pressure and altitude for damping and laterial acceleration for augmenting static directional stability. Initially, the lateral acceleration term was included in the system primarily to assist in turn coordination and was lagged through a large time constant. However, experience with high Mach inlet unstarts indicated that the pilot could not always tell which inlet had unstarted. The lagged time constant was, therefore, essentially removed so that static directional stability was augmented and more rapid rudder response to an unstart was achieved.

A critical design condition is the air loads on the all-movable vertical during an engine failure transient. The corrective action produced by the SAS is in the direction to increase the all-movable vertical loading relative to that produced by the externally-induced transient. Thus, sideslip angle minus vertical deflection, which is the local angle of attack at the vertical tail, must not exceed its structural design limit. The vertical tail design limit was conservatively established by simulation of an instantaneous engine seizure and unstart at maximum Mach number and maximum dynamic pressure. The final SAS configuration then had to provide the desired handling qualities without violating the structural constraints imposed by the engine-out transient and possible misapplication of rudder control by the pilot.

The yaw SAS meets the performance criterion of the Military Specification, MIL-F-8785 (ASG) as shown in Fig. 4.

Roll SAS

The roll axis presented no unique problems. The authority limit of the SAS servo is such that even a hardover failure is not catastropic. However, the roll SAS is the inner loop for all of the lateral autopilot modes. This, coupled with the desire to provide the necessary pilot relief and comfort, dictated that the system be at least dual.

SAS Redundancy and Logic

The pitch and yaw SAS utilized triple-redundancy in sensors, electronics, and gain scheduling. The servos for the pitch axis are two dual tandem series servos, each dual servo driving an inboard elevon. The yaw axis employs four series servos, whiffle tree summed in pairs, with each pair driving a separate vertical. The roll axis utilizes a dual redundancy configuration with dual sensors, electronics, and servos where one complete channel is used to drive each inboard elevon.

The gain scheduling is obtained from triple redundant differential pressure sensors and altitude switches. These are not part of the Central Air Data Computer, and comprise an entirely separate but simple sensing package. Because of the high reliance placed on the pitch SAS to provide static stability, an additional backup pitch damper (BUPD) is mechanized. This consists of a separate pitch-rate gyro and electronics located in a controlled environment that can be switched into either the A or B servos. This system has a fixed gain and is to be used only below 50,000 ft and at subsonic speeds. To date, there is no record of the BUPD ever having been used. Its purpose is to provide adequate handling qualities for refueling and landing in the event that the basic pitch SAS failed due to overheating of the normal pitch gyros. A block diagram of the pitch SAS mechanization is shown in Fig. 5. The yaw SAS is quite similar to the pitch SAS, but contains lateral acceleration terms and does not have a backup damper.

Logic and Logic Display

The sensor and electronic circuits of the yaw and pitch SAS's utilize triple redundancy in such a manner that a single failure is fail-operational with no change in system performance. Two channels, *A* and *B*, are functional; the *M* channel is used only as a reference or "monitor." A voting scheme selects the "disagreeing" channel and disengages it as shown in Fig. 5. A second or third failure depending on failure sequence results in total disengagement of that axis. After total disengagement of an axis, if either the *A* or *B* channels are still functional, the pilot can exercise a logic override switch and obtain single channel performance. The use of tandem servos in the pitch axis eliminated the need to double the gain in the remaining operational channel in order to maintain full system performance. However, the yaw axis electronic gain in the remaining operational channel is automatically doubled to maintain performance because of the whiffle tree summing mechanization of the series servos.

The servos in both the yaw and pitch channels are essentially quadruple, but with dual hydraulic supplies. The *A* hydraulic supply powers a right and a left servo that are both being driven by the *A* electronics. The *B* supply powers the remaining two servos which are driven by the *B* electronics. The left and right servos for each hydraulic supply are compared and if they fail to track, that channel is immediately disengaged. The remaining channel with its associated electronics then properly controls both the left and right surfaces with a gain equivalent to that of the complete system.

The roll SAS is mechanized as a simple dual system with one channel and servo for each side. A cross-monitor is employed in the servo feedback loops that disengages both channels in the event of disagreement. The disengagement is indicated by a failure light between the two channel switches. Disengaging and re-engaging both switches recycles the failure logic to verify the failure. The pilot then exercises logic override by switching off both channels and manually engaging one channel at a time to test and select the operational channel. The gain of this channel is automatically doubled.

In order for the pilot to evaluate failures in the pitch

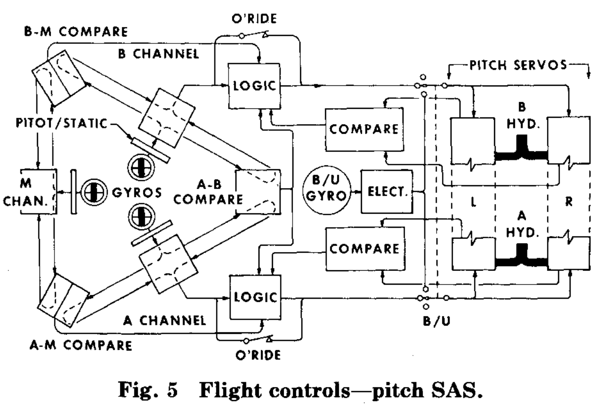

Fig. 5 Flight controls—pitch SAS.

Table 2 Failure indications

Lights (Yaw or Pitch)	Failure
A&M	A Electronics
B&M	B "
M	M "
A	A Servo
B	B "

and yaw SAS, a display of lights is presented on the Function Select Panel located on the right console. If any of the lights are on, the pilot pushes the illuminated buttons to recycle the logic. Should this fail to reinstate the channels, the pilot can then assess his situation in pitch and yaw as shown in Table 2 on the assumption that the light indication represents the first failure. Subsequent failures use the same lighting sequence and as a result, the particular type failure cannot necessarily be isolated.

A logic checkout switch is located adjacent to the function selector panel. This switch is activated during preflight checkout and a preprogramed test is automatically initiated to exercise the SAS logic and AFCS disengage function, to determine that all logic functions are operating properly.

Mach Trim

The F-12 series aircraft exhibits neutral or unstable speed stability characteristics up to approximately a Mach number of 1.5. The autopilot compensates in either Mach or equivalent airspeed-hold modes. However, caution must be exercised while on attitude hold by continually monitoring airspeed. The SAS-augmented manually-flown aircraft has an undersirable stick force feel characteristic to the pilot. To counter this, the proper pitch elevon gradient, as a function of Mach number, is fed to the control surface in the range between minimum speed and Mach 1.5 to provide speed-stable stick force gradients. Since the rate of change of surface required to achieve speed stabilization is quite low, the desired gradient is provided through the autopilot series autotrim actuator when the autopilot is disengaged. This function is not considered necessary for safety of flight and is, therefore, not redundant.

Automatic Pitch Warning (APW)

The F-12 series aircraft cruises at low-to-negative pitch stability levels which further decrease with increasing angle of attack. To prevent an unrecoverable pitch attitude, a redundant APW system warns of impending high-pitch attitude conditions. Angle of attack and pitch rate are scheduled with Mach number to provide a warning in the form of a stick shaker. The system utilizes the A and B gyros of the pitch SAS for a redundant measure of pitch rate. Angle of attack is not redundant since the angle of attack sensor on the pitot static boom is the only source of this parameter. The limit function is mechanized as a boundary limit on pitch rate as weighted by Mach number and angle of attack. To provide an indication of maneuver margin prior to broaching the limit function, the percent of the weighted pitch rate required to activate the shaker is presented to the pilot on the instrument landing system (ILS) bug on the left side of the attitude direction indicator (ADI). It is not displayed when the ILS or ILS approach mode is selected.

Autopilot

Autopilot modes are conventionally pilot relief modes requiring very little surface authority. In the pitch axis, the trim changes required as fuel is consumed, the aircraft is maneuvered, or speed is changed, are small due to the controlled low-static margin. The effect of these is further reduced by the use of automatic autopilot synchronization trim. Thus, in both pitch and roll, the autopilot signals always remain around zero and the signals can be limited such that a hardover failure will not be catastrophic. This has two advantages. First, the autopilot modes are not redundant since they are not required for safety of flight, and second, the conventional parallel servo for autopilot modes is not employed. Traditionally, the case for the parallel servo has been that in the event of a hardover autopilot failure, the pilot receives a cue from stick motion and then can quickly overpower the effect. With the limited authority of the autopilot, series servos can be utilized. Since the vehicle reaction to a failure is not severe, the pilot can make the necessary manual corrections with the stick until the autopilot can be disengaged.

The case for not using a parallel servo for the autopilot was strengthened by other factors. First, the mechanical advantage through the mixer to the servo was nonlinear, resulting in a difficult choice of pressure relief valve setting for overpower purposes. Another factor was weight-saving and reduced plumbing complexity. Reduced plumbing obviously enhances the reliability of the hydraulic system by avoiding additional potential leakage or line ruptures.

One autopilot mode that would require a full-authority servo, either parallel or series, would be a control-stick steering mode. This was avoided by providing disconnect steering instead. This is mechanized such that when the disconnect steering button is depressed on the stick grip, the control system reverts to SAS-augmented manual control with the existing autopilot modes disengaging. While the button is depressed, roll and pitch attitude signals are synchronized. Then, when the button is again released, the autopilot automatically re-engages to attitude hold, holding that attitude that existed at the moment of release. This type of pseudo control-stick steering has proven to be quite satisfactory and acceptable to the pilot.

Autopilot Modes

The autopilot modes in the F-12 series aircraft are Pitch Attitude Hold, Mach Hold, Roll Attitude Hold, and Heading Hold. The reconnaissance version also includes Equivalent Airspeed Hold and Automatic Navigation while the interceptor adds only the Altitude Hold mode. In normal operation, the vehicle performs most efficiently in a cruise climb at the design cruise Mach number. Since there is no auto throttle mode available, it is impossible to hold both Mach and altitude simultaneously. Thus, no particular benefit is normally derived from altitude hold. However, altitude hold is provided in the interceptor version to allow the vehicle to loiter in a holding pattern for landing or for quick deployment, at subsonic speeds, and at altitudes below 50,000 ft. The equivalent airspeed hold mode was developed from studies to determine optimum acceleration climbout and descent for the F-12 series aircraft.

The information required for these modes is provided by the air data computer, attitude reference system, heading reference system, and the inertial navigation system or the fire control system.

The Functional Development Process

The first step in the development process was to generate the gain schedules and control surface authorities. This was done by conventional analog computer techniques on selected flight conditions that adequately covered the flight regime. The original analysis assumed a rigid vehicle. Later, when structural aeroelastic data became available, the control laws were slightly modified by inclusion of aeroelastic filtering. The next step was to conduct a total equation simulation at the NASA Ames Research Center simulation facility. This simulation utilized the NE-2 two-axis moving base simulator and was developed in three phases. The first phase evaluated pitch characteristics only. The second phase expanded the simulation to the full six degrees of freedom for evaluation of the lateral directional characteristics. The final phase incorporated all of the predicted flexibility corrections to the aerodynamic data. During these simulations, Lockheed and Honeywell test pilots evaluated the handling characteristics. They were subjected to all possible situations including engine-out, loss of SAS, and loss of speed stabilization (Mach trim) throughout the flight envelope. These tests finalized the control laws and the redundancy requirements and indicated that the desired handling qualities could be attained.

To further evaluate the acceptability of the handling qualities, use was made of the NASA Variable Stability F-100 airplane. A variety of representative characteristics were evaluated by the same pilots that had flown the NASA Ames simulation. The results confirmed the acceptability of the design criteria and to some small degree provided pilot training.

To verify the design integrity of the system, an Iron Bird facility was constructed. The complete primary control system was installed in an oven with appropriate torque-tube and inertial loading of the hydraulics. The servos were driven by the first production SAS and autopilot and fed to an analog computer on which were programmed the aircraft equations of motion. The appropriate signals from the computer were properly conditioned and sent to the SAS and autopilot. A small fixed-base cockpit was provided and the equipment was subjected to the anticipated thermal environment. The design integrity was thereby established. In addition, this facility was used to evaluate the effect of SAS and autopilot failures to ensure that, even without pilot corrective action, structural design limits were not exceeded.

In a similar fashion, the aircraft equations were mechanized on an analog computer and the test pilots practiced control of engine-outs and other critical conditions using the actual vehicle immediately prior to the first flight.

The flight test program verified the predicted handling characteristics and demonstrated the design integrity of the system hardware. The actual flight testing of the F-12 series aircraft is the subject of Ref. 2.

Pilot Instrument Displays

The pilot of the F-12 series aircraft is provided with a variety of instrument displays exclusive of engine/inlet instruments to enhance his control of the aircraft. Many of these instruments are conventional, such as the normal pressure instruments for indicated airspeed, Mach number, altitude, and rate of climb. However, because of the high-altitude flight regime of the aircraft, these instruments are relegated to essentially a backup role to more accurate instruments and/or use at low altitide. The reason for this is instrument lag and accuracy at the very low ambient pressures. The situation is particularly critical for altitude and rate of climb. Instrument lag is primarily a function of volume of the pressure lines and instruments. Therefore, the pitot static probe has two sets of static pressure ports. One set is used exclusively by the Air Data Computer (ADC) and the Air Inlet Control (AIC) to minimize system volume and thereby lag. These systems require maximum accuracy, both statically and dynamically. The other set of pitot static ports is used for all other pressure instruments.

The intelligence for the primary instruments is derived from a Honeywell ADC, a very accurate force rebalance device which also includes compensation for Mach effects on the pitot static probe. Outputs from the ADC provide information for the primary speed-altitude instrument called the triple display indicator (TDI). This instrument presents equivalent airspeed (KEAS), altitude, and Mach number in digital form. In the Interceptor version, the TDI information plus vertical velocity is presented on vertical tape instruments.

Aircraft are normally designed to a maximum incompressible dynamic pressure or KEAS limit. In addition, optimum supersonic climb and descent performance is usually achieved at a constant KEAS. Conventional instrumentation presents indicated airspeed (IAS) since it is a simple pressure instrument. However, for the F-12 series aircraft, the Mach number effects cause considerable difference between IAS and KEAS and, with IAS only, the pilot would have to use charts and/or tables to fly the desired KEAS or establish the aircraft flight limitations. Therefore, it is quite apparent that KEAS is the superior presentation for the primary airspeed display.

Initially, the F-12 series aircraft were equipped with conventional vertical velocity indicators utilizing rate of change of static pressure as the input. However, at high cruise altitudes, reduced air pressure decreased instrument response and accuracy. The vertical speed indications might be less than one-third of the actual conditions and lag actual rates by several seconds. Indications at these altitudes were so inaccurate that the pilot tended to ignore the instrument and tried to use the rate of change of the digital altitude readout on the TDI. To improve vertical velocity indications, the conventional vertical speed indicator was replaced by an inertial lead vertical speed indicator (IVSI). The basic instrument is a combination of a conventional rate-of-climb indicator sensing static pressure changes and a mechanism sensitive to load factor. The latter provides an anticipation signal to drive the indicator in the right direction when either ascent or descent is initiated. The duration of its effect is only as long as the load factor is changing. Thus, for steady-state conditions, the indicator presents only the effects of the rate of change of the static pressure. This instrument is a definite improvement, particularly relative to sensing changes. However, the basic accuracy is still quite poor at high altitudes. By comparison, the tape vertical speed indication derived from the ADC on the interceptor version is more accurate than the IVSI and is acceptable for flight path control.

The conventional attitude director indicator (ADI), while providing adequate bank angle indications, has proven inadequate for precise pitch attitude control at high speeds. At high speeds, the F-12 series aircraft exhibit reduced sensitivity to roll attitude changes, but increased sensitivity to pitch attitude deviations. Since turning rate at a given bank angle is inversely proportional to forward velocity, no problem exists in the roll axis relative to flight path control. At F-12 cruise speeds, however, one degree of pitch attitude represents approximately 3000 ft/min rate of climb or descent. Thus, the pilot cannot use the ADI as an adjunct to flight path control and trim since the scale on the pitch angle indicator is such that small fractions of a degree cannot be accurately read.

To aid the pilot in trimming the pitch axis during high-altitude cruise and to maintain precise control of altitude during turns at high Mach numbers, a readout of inertial vertical velocity from the inertial navigation system is provided. This is not a separate instrument but is implemented through employment of the ILS pitch steering bar on the ADI when the ADI navigation mode is selected. The bar indicates zero vertical velocity when it is aligned with the miniature airplane. Full-scale deflection of the bar in this mode is approximately ±1 in. and represents a vertical velocity of approximately ±4000 ft/min. Pilot

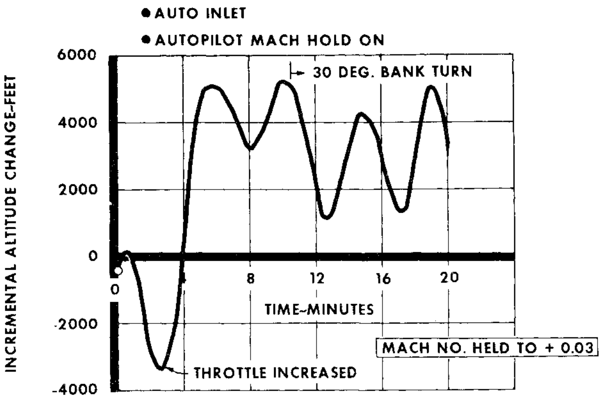

Fig. 6 High Mach Phugoid.

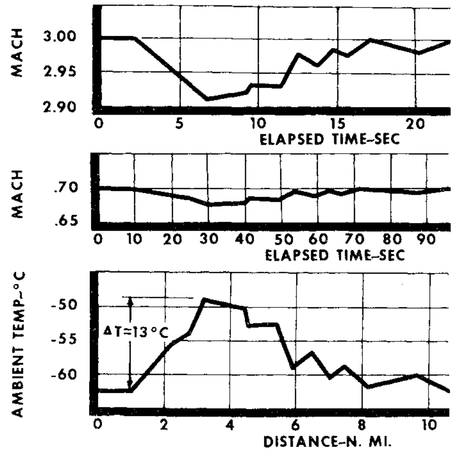

Fig. 7 Effect of temperature gradients on Mach number at constant velocity.

comments have indicated that this vertical speed indication in combination with the psuedo pitch rate indication presented on the ILS bug have been the two most important factors in establishing more accurate control of the aircraft at cruise conditions. In addition, by combining both functions on the ADI, pilot workload in terms of instrument scan has been reduced.

Other instruments pertinent to proper control of the aircraft are: a conventional horizontal situation indicator (HSI), a normal accelerometer, an angle of attack indicator, pitch, yaw, and roll trim indicators, and a center-of-gravity indicator. The center of gravity is scheduled automatically to approximately the optimum position by automatic fuel sequencing for a normal supersonic flight profile. However, for other flight profiles or emergency conditions, the pilot can transfer fuel forward or aft to establish any desired center of gravity.

Flight Experience

The F-12 series aircraft flight test program verified the acceptability of the handling qualities and the design integrity of the control system. The high reliability of the triple-redundant pitch and yaw SAS was found to exceed estimates as previously discussed. However, at least three distinct flight control problems were encountered in the flight test program which were not anticipated. These problems all occurred at high Mach number and were specifically: a long-period lightly damped phugoid mode, an oscillatory divergence of the Dutch roll mode with yaw SAS inoperative, and poor-to-unacceptable performance of the autopilot Mach hold mode.

The high Mach phugoid is characterized by large-altitude excursions at relatively constant speed as illustrated in Fig. 6. The conditions for this particular case are automatic inlet control and Mach hold engaged. Note that a throttle increase and initiation of a turn continue to excite this mode. This case tends to be an extreme and pilot technique or other autopilot modes can reduce the altitude excursions. The NASA F-12 flight research program has explored the effect of inlet operation, SAS and autopilot operation, and Mach trim on this mode and their results are reported in Ref. 3. Continued exploration is required in this area since this mode is adversely affected by airframe/propulsion system interactions.

An oscillatory divergence of the Dutch roll mode with yaw SAS inoperative was found to exist at the higher Mach numbers due to modulation of the inlets as a function of sideslip angle. This causes thrust/drag gradients that resulted in yawing moments which opposes the inherent aerodynamic damping. This phenomena is also reported in Ref. 3. No appreciable effect of this destabilizing action of the inlets was observed with the yaw SAS engaged. This illustrates the complete dominance that the yaw SAS has over the unaugmented aircraft characteristics.

The aircraft and engine inlets are designed for maximum flight efficiency at optimum cruise Mach number, and a good autopilot Mach hold mode is desirable to minimize Mach deviations. It is very difficult, however, to achieve a good Mach hold at F-12 type cruise speeds. At these speeds, a normally mild temperature gradient becomes very sharp. Since Mach number is temperature-dependent, a sharp gradient causes abrupt Mach variations and is seen by the pilot as "cash registering" of the digital Mach readout on the TDI. The effects of a typical temperature gradient are presented in Fig. 7 for a vehicle flying at Mach 0.7 and Mach 3.0. This particular temperature gradient was experienced during a U-2 flight. As indicated, the temperature gradient has relatively little effect at Mach 0.7. It is traversed in approximately 60 sec and the maximum Mach deviation is -0.02. However, at Mach 3.0, the gradient is traversed in approximately 15 sec and the maximum Mach deviation is -0.09. The initial deviation of -0.09 Mach is equivalent to a deceleration of 0.6 *g* if the aircraft velocity were to have actually changed. The result of atmospheric temperature variations of this type on a tight autopilot Mach hold mode is the command of large attitude changes and, therefore, load factor changes which are intolerable to the pilot. To relieve these effects, the gains of the Mach hold autopilot mode were reduced and a *g* limiting feature was added during flight test. This improved the ride quality, but at the expense of wider deviations in Mach number. A completely satisfactory solution to this problem is yet to be attained and the aircraft is flown primarily on the autopilot pitch attitude hold mode and rarely on Mach hold at maximum design cruise speed.

Conclusions

The F-12 series aircraft have demonstrated that the problems of high Mach supersonic cruise flight are not insurmountable. It has been shown that systems can be designed to withstand harsh environments and with the reliability necessary for control-configured-type vehicles.

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