FLIGHT EXPERIENCE WITH ALTITUDE HOLD AND MACH HOLD AUTOPILOTS ON THE YF-12 AIRCRAFT AT MACH 3

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SUMMARY

In order to obtain maximum range when operating aircraft at high altitude and high Mach number conditions, precise control of both flightpath and speed is necessary. However, experience with the XB-70, YF-12, and Concorde airplanes has shown that simultaneous control of flightpath and speed is extremely difficult at these flight conditions. Therefore, one aspect of the YF-12 program was to investigate methods to improve the altitude and Mach hold capabilities for high supersonic and hypersonic aircraft.

In this study, the altitude hold mode of the YF-12A airplane was modified to include a high-pass-filtered pitch rate feedback along with optimized inner loop altitude rate proportional and integral gains. An autothrottle control system was also developed to control either Mach number or KEAS at the high-speed flight conditions.

Flight tests indicated that, with the modified system, significant improvements were obtained in both altitude and speed control, and the combination of altitude and autothrottle hold modes provides the most stable aircraft platform thus far demonstrated at Mach 3 conditions.

INTRODUCTION

Although accurate control of altitude and Mach number becomes increasingly important in achieving maximum range performance at high altitude, high Mach number flight conditions, experience with the XB-70 (ref. 1), YF-12 (ref. 2), and Concorde (ref. 3) airplanes has shown that precise control of flightpath and speed become more difficult at these conditions. Decreased aircraft stability, low static pressures, and the presence of atmospheric disturbances are all factors that contribute to this degraded control. The combination of high altitude and high speed also contributes to an unfavorable balance between kinetic and potential energy, thereby requiring large altitude changes to correct for small Mach number errors when flying a Mach hold mode using the elevator control.

This report covers one aspect of the YF-12 program directed at developing satisfactory altitude-hold and autothrottle-Mach-hold autopilot modes for operation at high altitude, Mach 3 flight conditions. Both flight-test results and simulator studies (ref. 4) are presented and comparisons are made using various control schemes.

SYMBOLS

Physical quantities in this report are given in the International System of Units.

a_n	normal acceleration at center of gravity, g
h	pressure altitude, m
KEAS	knots equivalent airspeed
M	Mach number
PLA	power lever angle, deg
p_s	static pressure, N/m^2
p_{t_2}	stagnation pressure, N/m^2
s	Laplace operator
α	angle of attack, deg
Δ	incremental change
ΔT	temperature change, K
δ_e	average elevon deflection, deg
θ	pitch angle, deg
φ	roll angle, deg

Subscripts:

e	error
2	compensated location on nose boom
3	location 0.2667 meter aft of stagnation pressure port on nose boom

A dot over a quantity denotes the time derivative of that quality.

FLIGHT SYSTEM

Aircraft Description

The YF-12 airplane (figs. 1 and 2) is an advanced, twin-engine, delta-wing aircraft designed for long-range cruise at speeds greater than Mach 3 and altitudes greater than 24,000 meters.

The airplane has two axisymmetric, variable-geometry, mixed-compression inlets, which supply air to two J58 engines. Each inlet has a translating spike and forward bypass doors to control the position of the normal shock in the inlet. An automatic inlet control system varies the spike and bypass door positions to keep the normal shock in the optimum location. The pilot may also manually control the spike and bypass doors.

Two nacelle-mounted, all-movable vertical tails (rudders) provide directional stability and control. Each rudder is canted inward and pivots on a small stub section attached directly to the top of the nacelle. Two elevons on each wing, one inboard and one outboard of each nacelle, perform the combined functions of ailerons and elevators.

The airplane is normally operated with the stability augmentation system (SAS) engaged to provide artificial stability in pitch and yaw and to provide damping in pitch, yaw, and roll.

A more complete description of the aircraft is given in reference 5.

Air Data Computer

The autopilot obtains Mach number and altitude information from an electromechanical air data computer (ADC). The ADC, described more completely in reference 4, receives static and total pressure data from a compensated nose boom installation. The static pressure threshold of the ADC is approximately 1.676 $N\text{-}m^2$, which corresponds to an altitude change of 3.67 meters at a flight altitude of 23,662 meters. The effective lag of the static pressure system is approximately 1.5 seconds at this flight condition.

ALTITUDE AND MACH HOLD CONTROL SYSTEM

The original altitude hold control system, shown in figure 3, was designed around a pitch SAS and an attitude hold loop. The altitude hold outer loop commands attitude changes that are proportional to altitude rate, altitude error, and the integral of altitude error. Both the pitch SAS and attitude hold loops perform satisfactorily.

Since the altitude hold mode of the autopilot receives altitude information from the ADC, any peculiarities in the air data parameter, p_s, show up in the altitude hold capabilities of the autopilot. The location of the nose boom static pressure source can have a significant effect on the altitude hold operation. The static pressure source, p_{s_2} (fig. 4), which is on the compensated portion of the nose boom, is used by the ADC. Compensated static pressure ports are located to minimize static pressure position errors in the transonic region, but they are sensitive to angle of attack, as shown in figure 5. At a trim angle of attack of 3°, the $\Delta p_{s_2}/\Delta\alpha$ ratio is zero, but at 5° a typical value of $\Delta p_{s_2}/\Delta\alpha$ is -22.02 N/m^2. The variation in the $\Delta p_{s_2}/\Delta\alpha$ ratio and resulting variation in indicated altitude is caused by angle of attack changes.

The conventional Mach hold control system (fig. 6) is an outer loop of the basic pitch SAS and attitude hold loop. The Mach hold autopilot receives Mach number information from the ADC and commands attitude changes proportional to the sum of Mach error plus the integral of Mach error.

The Mach hold mode of the autopilot receives Mach number information from the ADC; therefore, the same static pressure angle-of-attack effects previously discussed also affect the Mach number information. At an airspeed of Mach 3.0 and an altitude of 23,000 meters, the Mach number sensitivity, $\Delta M/\Delta\alpha$, is approximately 0.01 Mach per degree angle of attack.

SIMULATION SYSTEM

A combined analog/digital computer simulation was first used to duplicate and analyze problems with the original autopilot and then to investigate the effects of system modifications or new system designs. A perturbation model representing the aerodynamics and aircraft performance characteristics was programed for a flight condition of Mach 3.0 and altitudes greater than 21,336 meters. The simulation was a modification of that described in reference 6 and included the three longitudinal degrees of freedom, the inlet geometry effects on aircraft motion, inlet operation characteristics up to the unstart boundary, the characteristics of the afterburning mode of the engines, and the variation of density with altitude. An aircraft model with quasi-static flexibility corrections was used. No structural modes were simulated and all control system dynamics above 5 hertz were eliminated. The simulation could accept a variety of continuous and discrete input disturbances and could prove time histories of any quantity in real time.

Altitude Hold

The baseline altitude hold mode of the YF-12A autopilot was designed to operate at altitudes less than 18,288 meters. Preliminary evaluations of the altitude hold mode at altitudes exceeding 21,336 meters found that its operation varied from day to day. Occasionally, altitude could be held reasonably constant; at other times, it diverged in an unacceptable manner.

Figure 7 illustrates good altitude control at approximately Mach 3.0 and 23,622 meters. The pilot described the atmosphere as stable, as evidenced by the ease of holding the Mach number and altitude conditions. The low frequency limit cycle in altitude is due to the ADC static pressure threshold. The high frequency oscillatory characteristics in δ_e were due to the sensitivity of static pressure to angle of attack.

An example of unacceptable altitude hold control at Mach 3.0 and 23,622 meters is presented in figure 8. The pilot described the atmosphere as unstable, as evidenced by the difficulty in holding altitude and by the jumps in the indicated Mach number. Although atmospheric disturbances apparently induced the erratic altitude behavior on this occasion, other types of disturbances or untrimmed conditions could also initiate the altitude instability. The high frequency oscillations were due to the sensitivity of static pressure to angle of attack. As angle of attack increased in proportion to a_n, $\Delta p_{s_2}/\Delta\alpha$ increased negatively and the short period motion became divergent. When angle of attack decreased, $\Delta p_{s_2}/\Delta\alpha$ decreased and the short period motion damped.

Parametric studies of static pressure sensitivity to angle of attack, as well as the effect of autopilot gains on altitude hold performance, are provided in reference 4.

Improved Altitude Hold

The first phase of the autopilot improvement program involved tuning the baseline autopilot to see if satisfactory performance could be obtained at altitudes greater than 21,336 meters.

The simulator altitude hold gain optimization studies were initially performed with $\Delta p_{s_2}/\Delta\alpha$ set at zero. In this configuration, good altitude hold was obtained on the simulator with the original altitude rate gain, one-half the original altitude error gain, and one-fourth the original integral of the altitude error gain. In subsequent simulation studies, compensation in the static pressure angle-of-attack sensitivity was achieved by including the high-pass-filtered pitch rate feedback shown in figure 9. Bending compensation was added to eliminate structural interaction, and high frequencies were cut off before the signal was summed with $\Delta\theta$ and sent to the autopilot.

Typical flight-test data with the modified autopilot are shown in figure 10. After engagement, the autopilot kept altitude constant to within ±7.62 meters for the 4-minute duration of the run. The long period, 35-second, low amplitude oscillation was due to the threshold of the ADC. As illustrated, there was no degradation of altitude hold, even though 0.4 Mach was lost.

The high frequency (one cycle per second) low amplitude (±0.2°) oscillation of the elevon was a short period limit cycle produced by the nonlinear characteristics of the rate gyro used in the high-pass-filtered pitch rate autopilot loop. (The gyro used is noted for reliability, not for resolution or linearity.)

A typical YF-12 experimental flight, made for purposes other than control systems research, consists of brief 1- to 2-minute periods of flight at stabilized

Mach numbers and altitudes for as many conditions as can be fitted into the flight plan. For these flights, pilots have found the modified autopilot valuable for rapidly obtaining and holding altitude. Figure 11 illustrates a typical engagement of the modified autopilot with an initial rate of descent of approximately 400 meters per minute.

The atmosphere was stable for both modified autopilot examples. However, any latent aircraft control system instabilities would probably have been excited by the deceleration shown in figure 10 or by the initial rate of descent condition shown in figure 11.

With the altitude hold mode engaged, the pilot's Mach hold task was easy. In addition to improving the quality of each run, it was estimated that, because of the time saved in establishing and maintaining altitude, using the modified autopilot, 10 percent additional data could be obtained on each flight. Reference 4 provides a more complete evaluation of the altitude hold autopilot program.

Mach Hold

Conventional Mach hold.—The conventional Mach hold mode of the YF-12C autopilot (fig. 6) was designed to operate over the entire Mach number range of the aircraft. At speeds greater than Mach 2.0, the desired Mach number could be held quite accurately to within ±0.02 Mach for wings-level conditions. In turns, the quality of Mach control was generally reduced, particularly at the higher Mach numbers. Although the problem of holding Mach in the turn did not receive much attention, it appears that the primary cause is related to the automatic navigation mode of the autopilot, which operates through the ailerons and couples with the longitudinal axis in turning flight. An example of the performance of the conventional Mach hold mode at Mach 2.85 is presented in figure 12. The first 7 minutes were flown with wings level and the speed was held to within ±0.02 Mach of its value at engagement. However, the ride was quite rough, as evidenced by the $\pm 0.2g$ normal acceleration levels and by the peak-to-peak altitude change of 1066 meters. Seven minutes of data were obtained in turning flight with a bank of approximately 34°. In the turn, the quality of Mach hold was slightly degraded ($\Delta M \approx \pm 0.025$) as were the ride qualities ($\pm 0.35g$ normal acceleration). A peak-to-peak altitude change of 610 meters was encountered during the turn.

It is obvious from the Mach hold example in figure 12 that although the Mach number control was fairly good, the associated ride qualities in terms of normal accelerations were unacceptable. Furthermore, the altitude changes could be unacceptable from an air traffic control standpoint.

The effect of static pressure source sensitivity to angle of attack in the Mach hold mode is presented in reference 4 for the YF-12A aircraft, which has a slightly different Mach hold control scheme.

Autothrottle Mach and KEAS hold.—The second major objective of the autopilot improvement program was to develop an autothrottle control system which could control either Mach or KEAS and which would be compatible with the improved altitude hold control system. The initial autothrottle control studies were evaluated on the previously discussed NASA simulation system. A functional diagram of the autothrottle control system implemented on the aircraft is presented in figure 13.

Either Mach or KEAS from the ADC and pitch attitude are gain-adjusted and summed to provide the control reference signal. The input signals were filtered to reduce noise, and additional lead was provided by the high-pass filter. The output of a proportional-plus-integral logic network was used for the actuator command signal. In turn, throttle control was accomplished by a constant rate actuator moved in a discrete fashion by the switching relay commands.

Figure 14 provides a simulation comparison of various autopilot control modes at Mach 3.0 and 22,100 meters for a mild temperature variation of no more than 2.4 K peak to peak over a period of 9 minutes (ref. 7).

The response of the attitude hold mode to such a temperature variation is shown in figure 14(a). Attitude, which is not shown, is essentially constant ($\Delta\theta = \pm 0.03°$), but altitude drifted off significantly, and Mach number was uncontrolled. The ride was smooth for this control mode.

Attitude hold is the inner loop for both the altitude hold and conventional Mach hold modes. The altitude hold simulation run is presented in figure 14(b) which shows that altitude was held accurately to within 15 meters peak to peak. The ride was good, but Mach number drifted off.

The conventional Mach hold simulation run is presented in figure 14(c). Airspeed was held reasonably accurately to within ±0.01 Mach, although control of the high frequency Mach variations was slight. The associated altitude variation was large (336 meters peak to peak), especially in view of current air traffic control altitude assignments. The resulting variations in normal accelerations were 0.12g peak to peak. Although this level was probably not disturbing in terms of ride qualities, it was significant in view of the mildness of the temperature variation.

The simulation run of altitude hold combined with the autothrottle Mach hold system is shown in figure 14(d). Mach number was held well, but not noticeably better than with the conventional Mach hold. However, with the autothrottle, altitude was controlled accurately and ride qualities improved. Accurate control of the high frequency Mach number error was dependent on the thrust modulation capability of the autothrottle system, which is low for this airplane.

Figure 15 shows the flight-test data obtained at Mach 3.0 and 22,100 meters with the autothrottle in Mach hold and the pitch autopilot in altitude hold. The atmospheric conditions during this run were stable or smooth. The systems capabilities were tested a number of ways in this example. The autothrottle was engaged in Mach hold while stabilized in a 36° bank turn. Shortly after engagement, the aircraft was rolled to wings level. Approximately 2 minutes into the autothrottle run, the pilot commanded a 0.023 Mach reduction; however, Mach was not controlled as rapidly because the power levers were at their minimum authority. During the stabilized portions of the time history, speed was held to within approximately ±0.01 Mach of its desired value. The altitude hold mode was on throughout the autothrottle run. The desired altitude was perfectly maintained prior to and after the rollout, although 24.4 meters were gained during the rollout transition. It should be noted that the altitude was held accurately even though rather large power changes were commanded by the autothrottle Mach hold system. The ride qualities, indicated by the normal acceleration, were good.

A second example of Mach hold autothrottle is presented in figure 16. In this case, the altitude hold and autothrottle Mach hold were engaged with wings level. After approximately 1.5 minutes, the aircraft was rolled into a 30° bank turn and remained in the turn for the duration of the autothrottle run. Speed was controlled to approximately ±0.01 Mach, and altitude was controlled to within 16 meters peak to peak after the initial engage transient.

The autothrottle also has a KEAS hold mode which, when used in conjunction with altitude hold, theoretically should have been equivalent to Mach hold. In this configuration, KEAS could be controlled to within ±2 knots of the desired airspeed.

Thus far, pilots' comments on autothrottle experience have been quite favorable. Except for short intervals, the autothrottle system could control Mach or KEAS more accurately than the pilot.

The autothrottle was evaluated with two different speed actuators. The slow and fast actuators covered the same throttle range in 20.5 seconds and 3.48 seconds, respectively. No significant difference in control quality was apparent; however, the slow actuator was desirable since it was much less active than the fast actuator.

To date, our flight experience has demonstrated that the combination of altitude hold and autothrottle Mach hold provides the most stable aircraft platform capability ever demonstrated at high altitude, Mach 3 conditions.

CONCLUSIONS

Good altitude hold was demonstrated at high altitudes using existing autopilot concepts and hardware with only minor modifications. These modifications added a high-pass-filtered pitch rate feedback to compensate for angle-of-attack sensitivity and to improve the blend of altitude rate, error, and integral gains. Static pressure source sensitivity to angle of attack was found to have a significantly adverse effect on altitude hold.

Accurate Mach control was demonstrated at high speeds using an autothrottle control system. The combination of altitude hold and autothrottle Mach hold provided the most stable aircraft platform ever demonstrated at high altitude, Mach 3 conditions.

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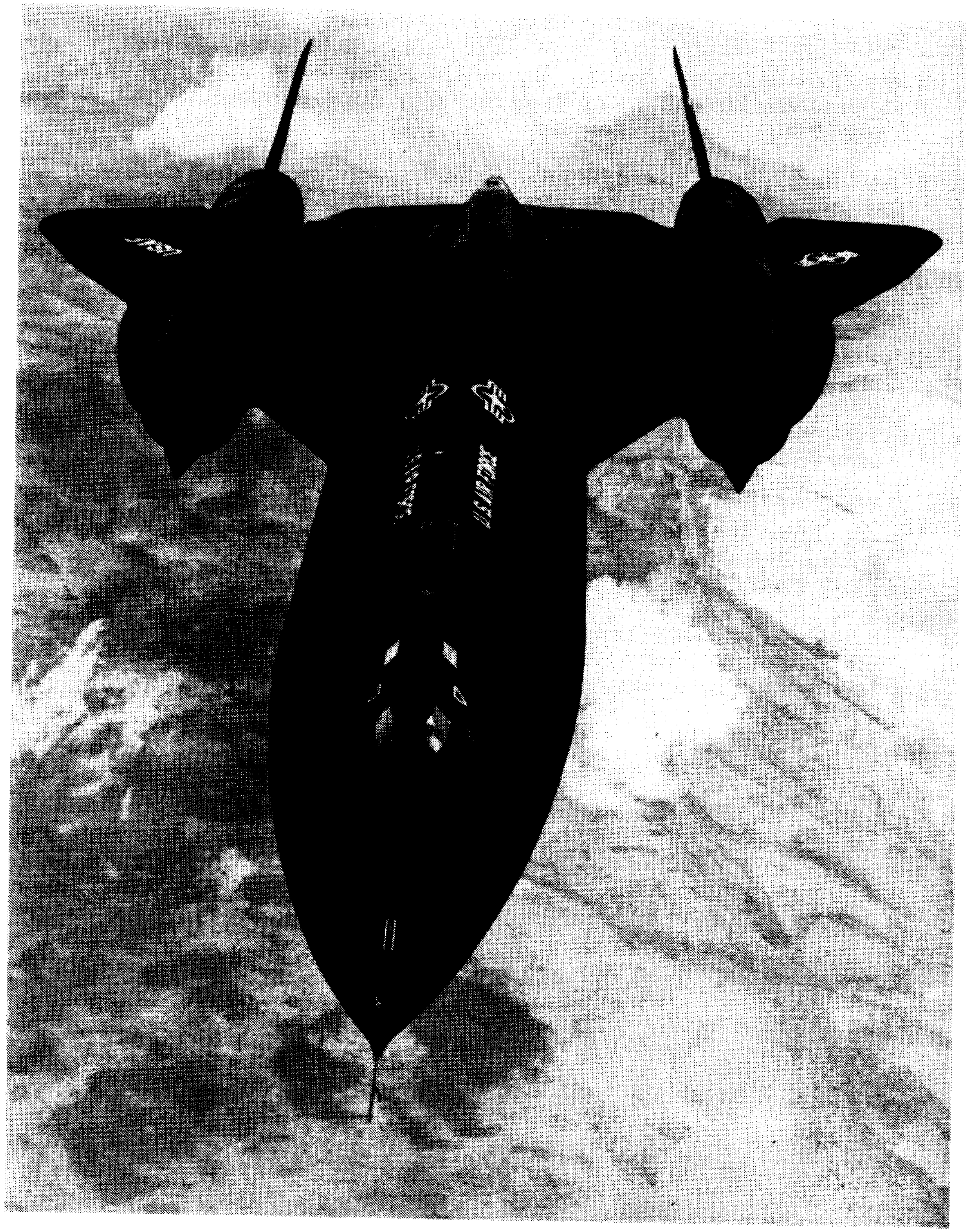


Figure 1.—YF-12C airplane.

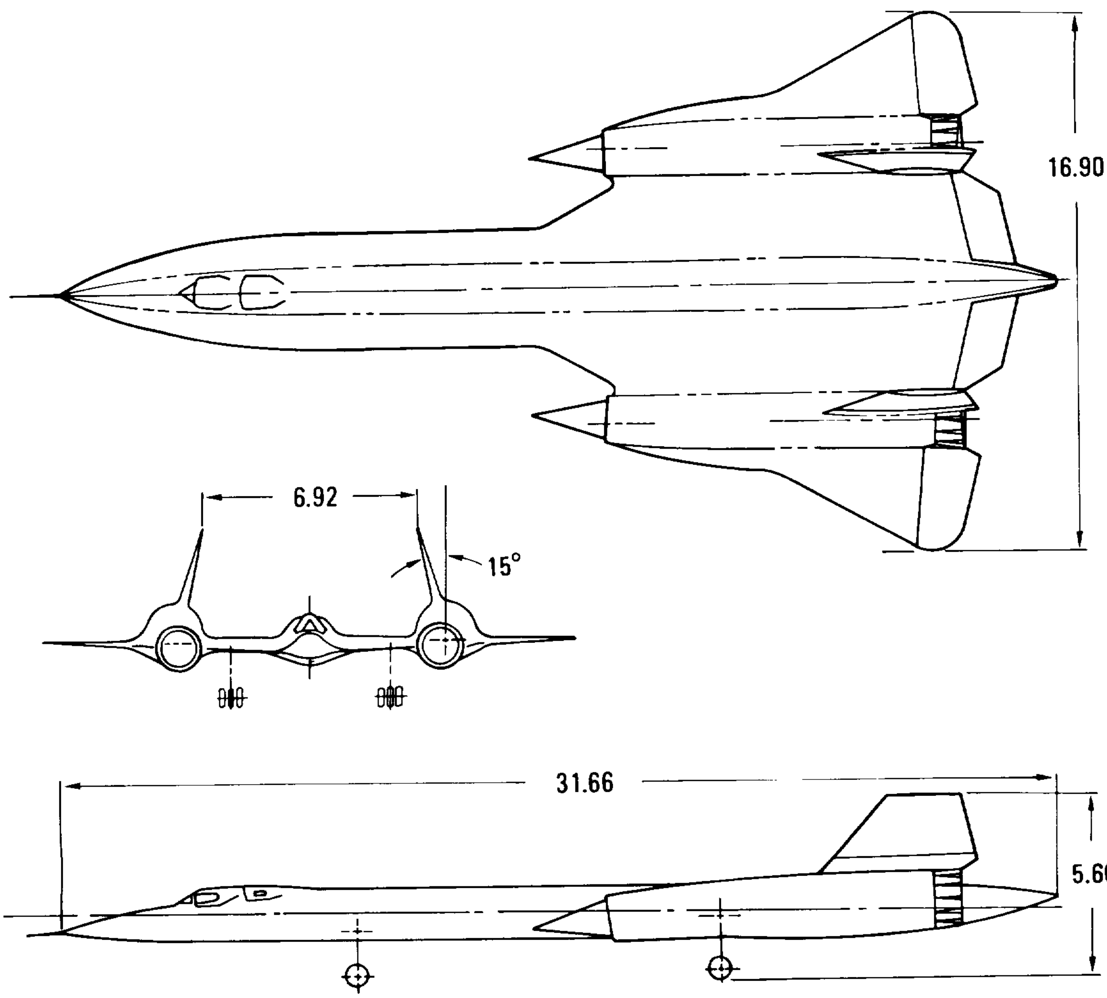


Figure 2.—Three-view drawing of the airplane. Dimensions are in meters.

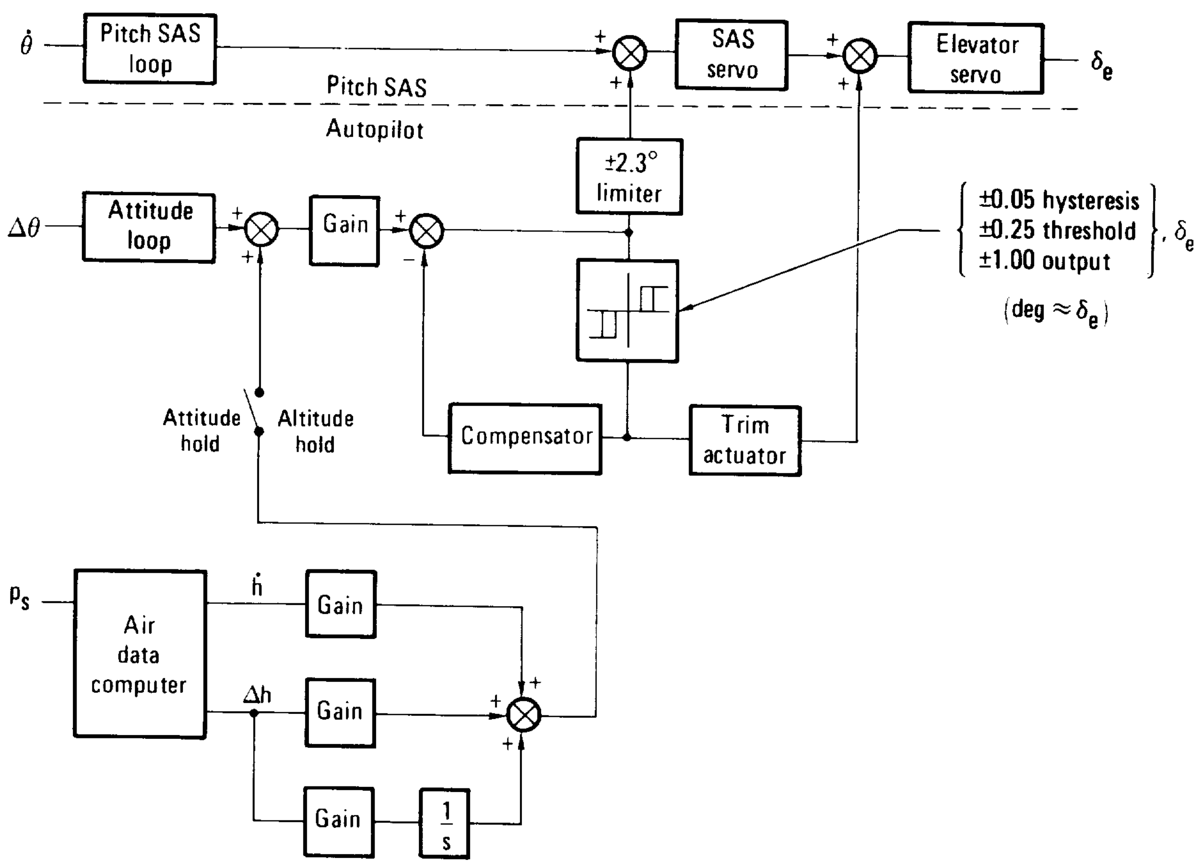


Figure 3.—Original altitude hold autopilot block diagram of the YF-12A airplane.

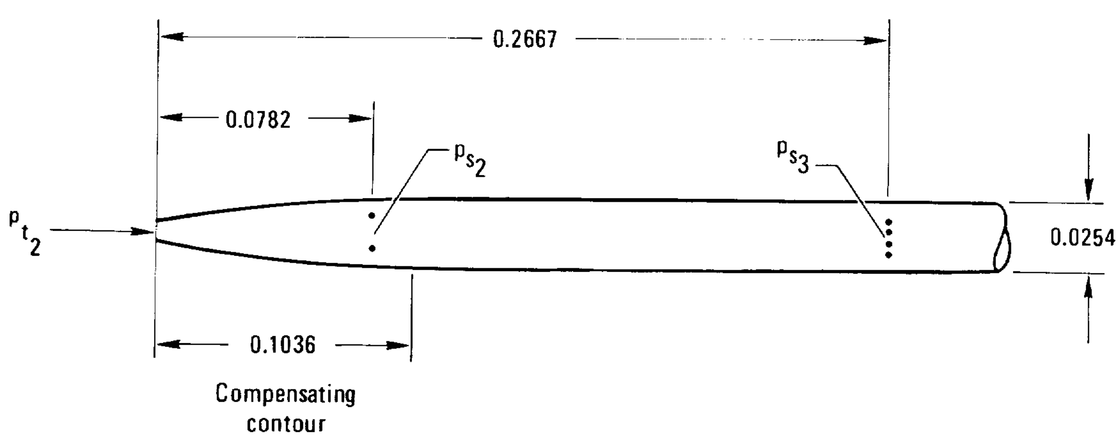


Figure 4.—Static pressure source locations on nose boom. Dimensions are in meters.

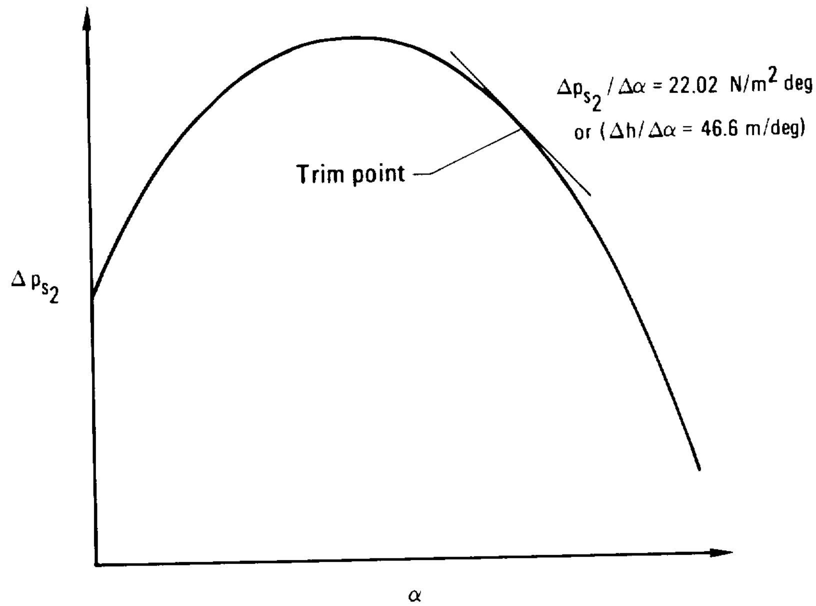


Figure 5.—Variation of static pressure error with angle of attack. M ≈ 3, h ≈ 23,622 meters.

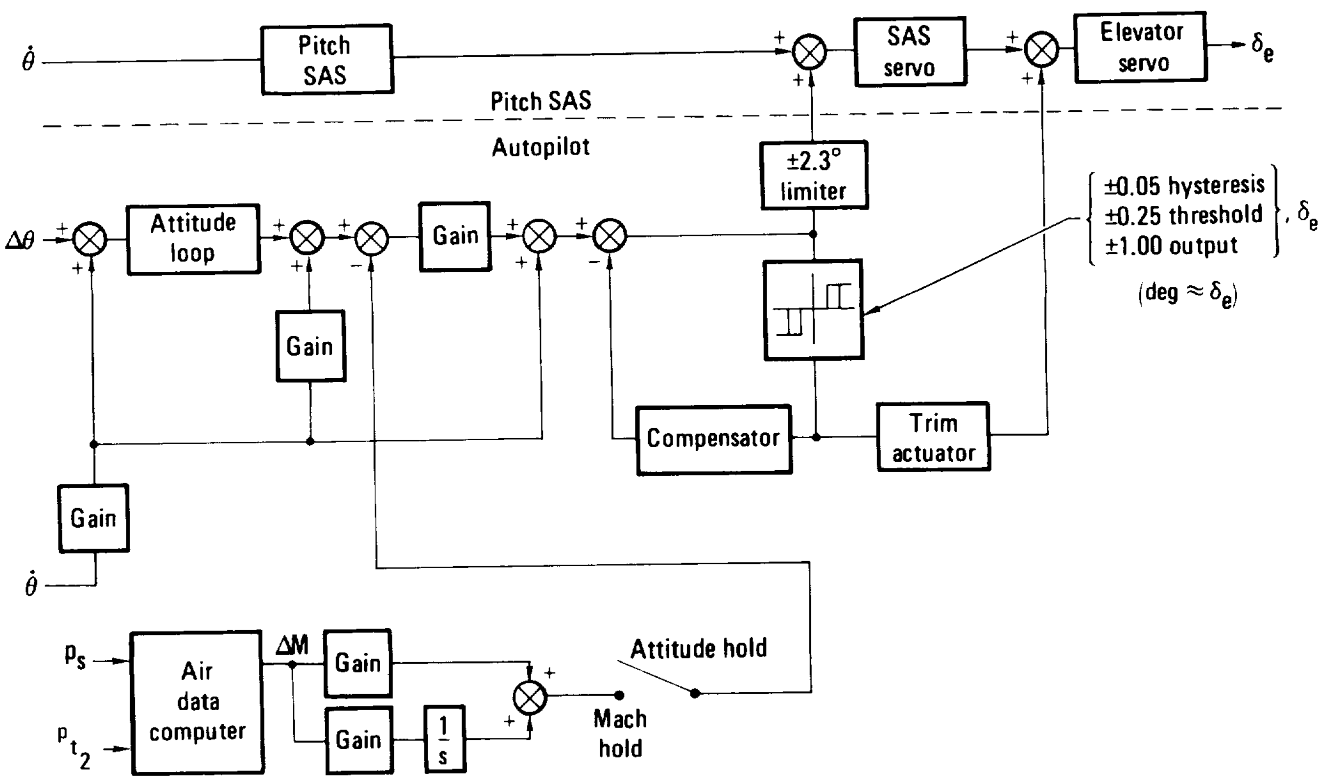


Figure 6.—YF-12C Mach hold control system. h > 15,240 m.

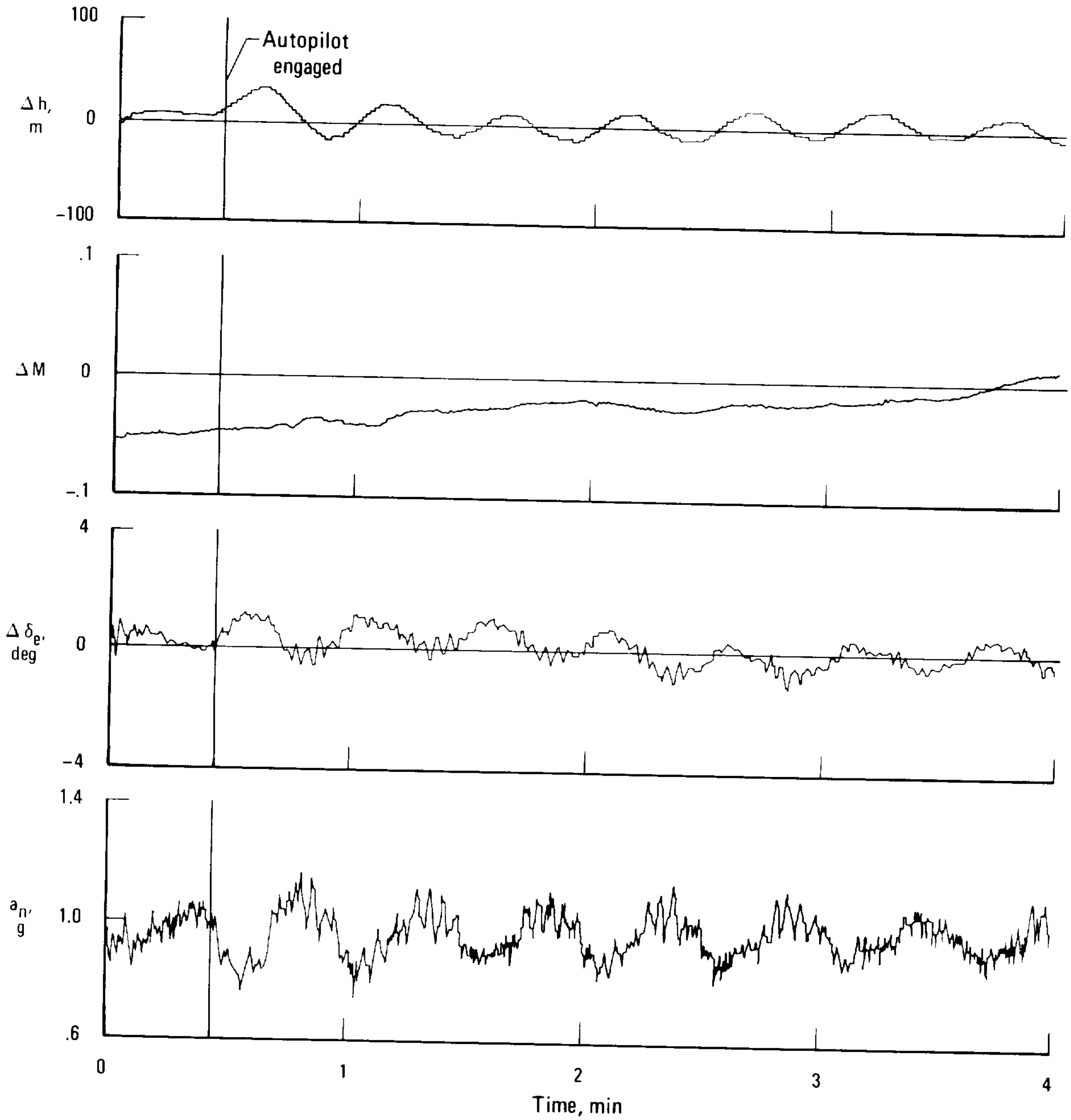


Figure 7.—Good baseline altitude hold with stable atmosphere. $M \approx 3$, $h \approx 23{,}622$ m.

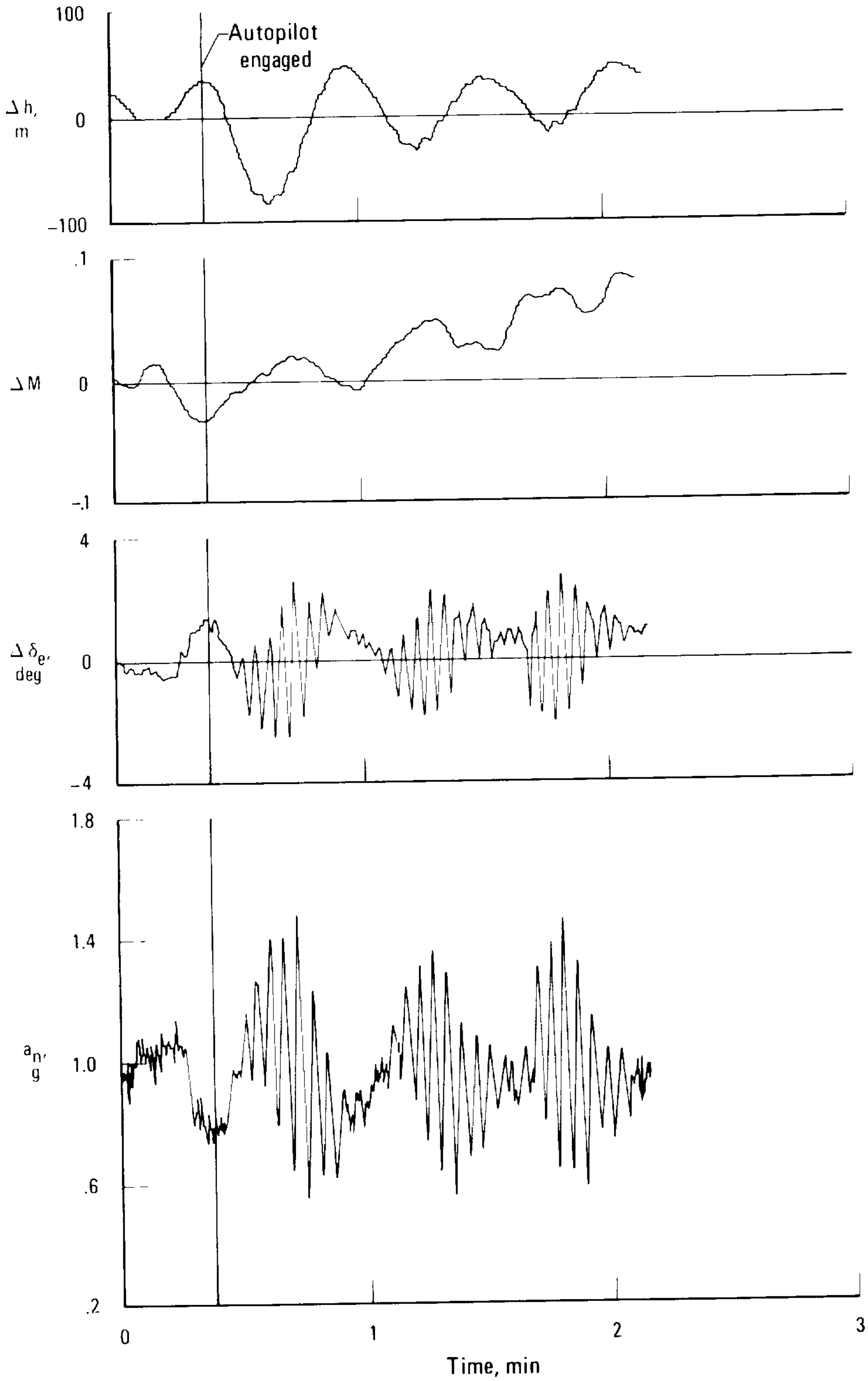


Figure 8.—Unacceptable baseline hold with unstable atmosphere. $M \approx 3$, $h \approx 23{,}622$ m.

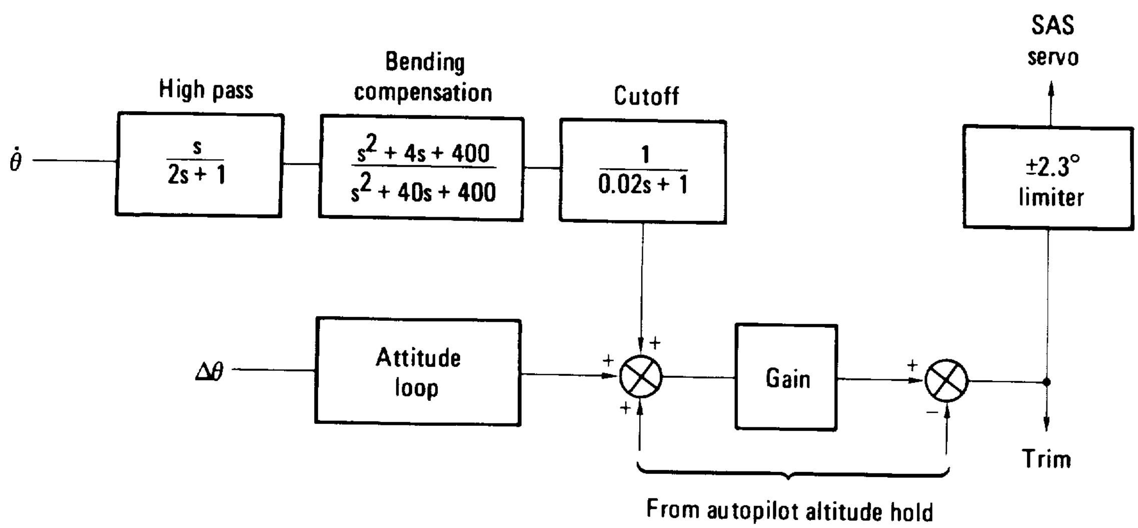


Figure 9.—High-passed pitch rate loop used to compensate for sensitivity of static pressure to angle of attack (fig. 4).

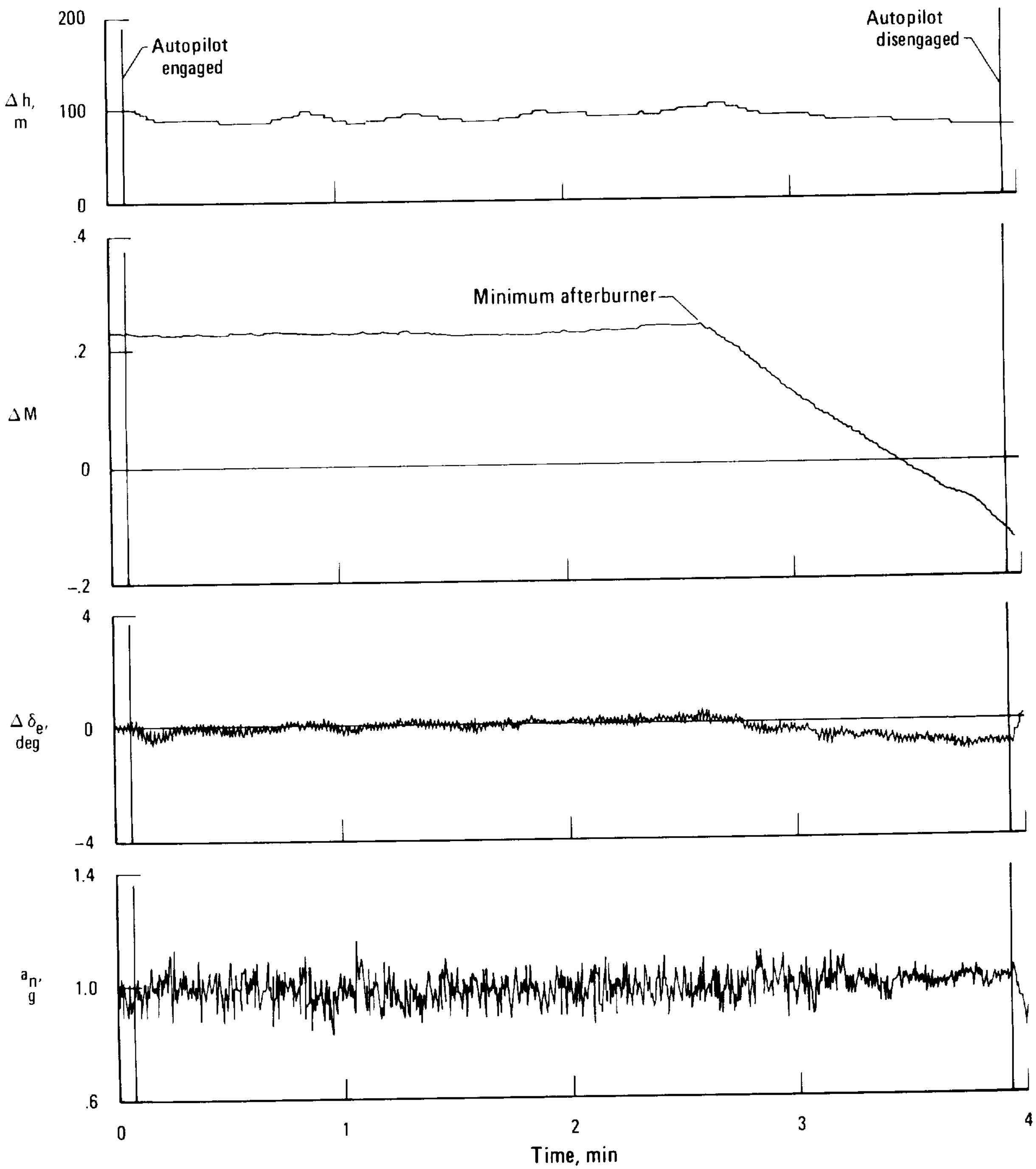


Figure 10.—Performance of modified autopilot. $M \approx 3$, $h \approx 23{,}622$ m.

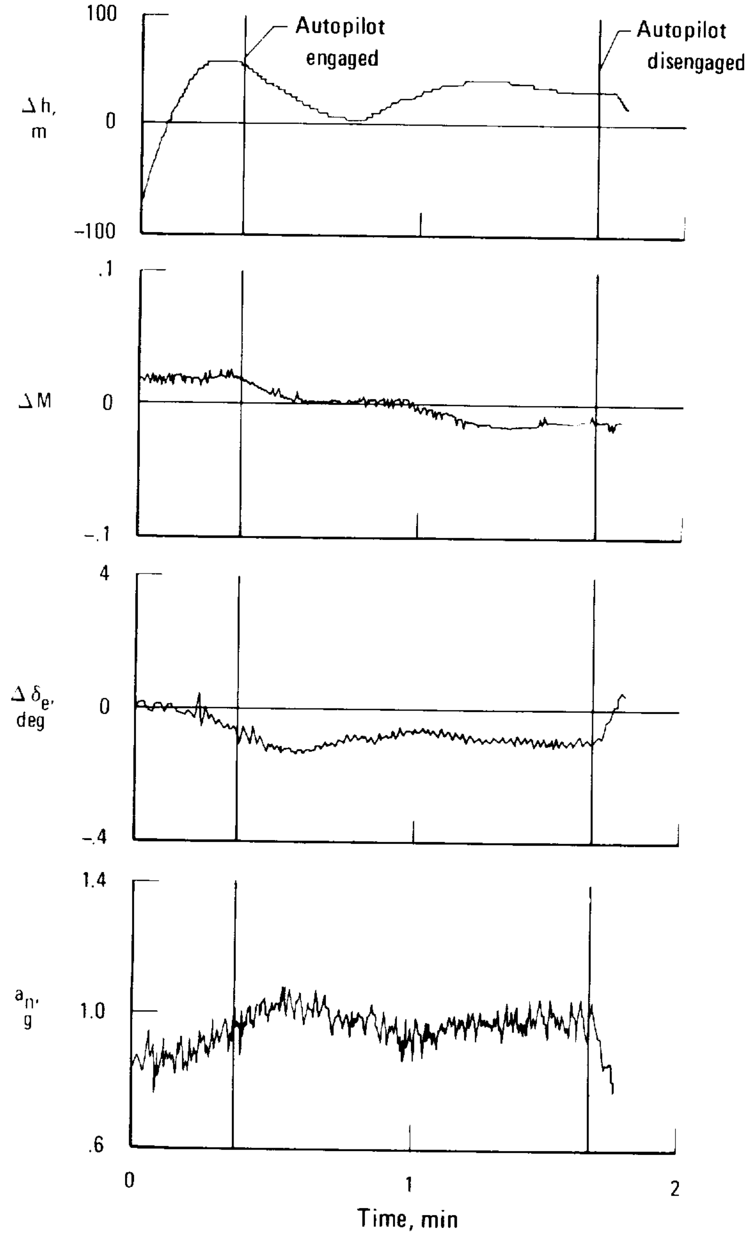


Figure 11.—Performance of modified autopilot with an initial rate of descent. $M \approx 3$, $h \approx 23{,}622$ m.

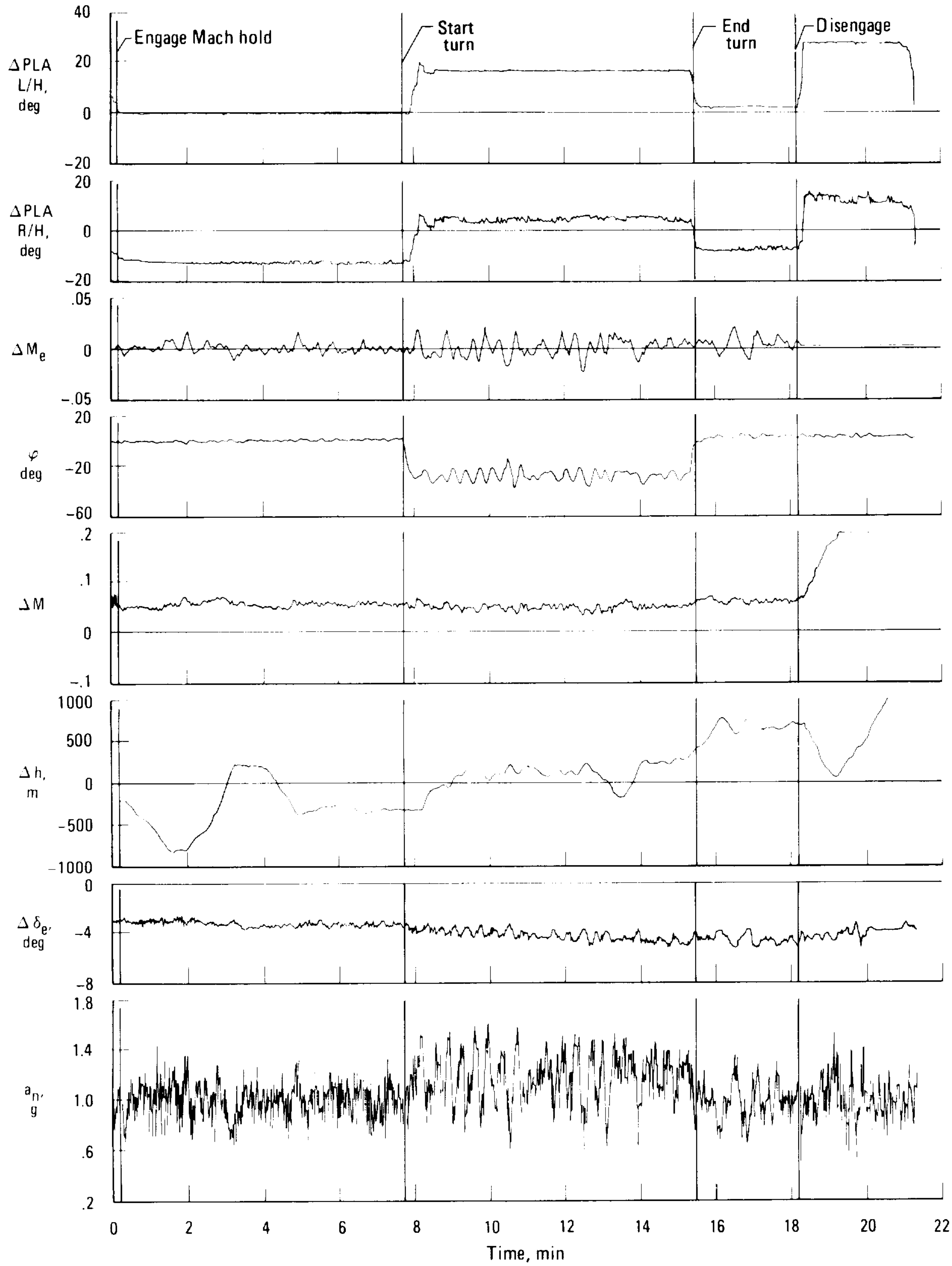


Figure 12.—Conventional Mach hold of the YF-12C airplane. Mach 2.85.

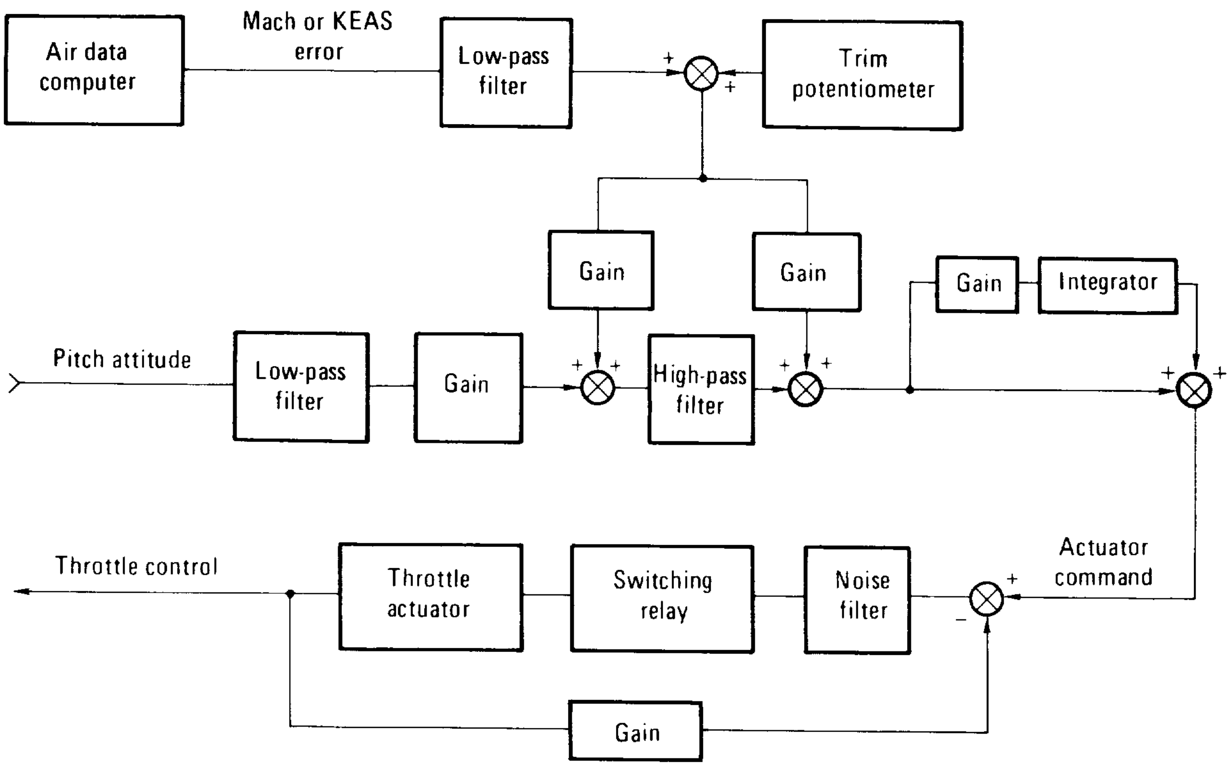
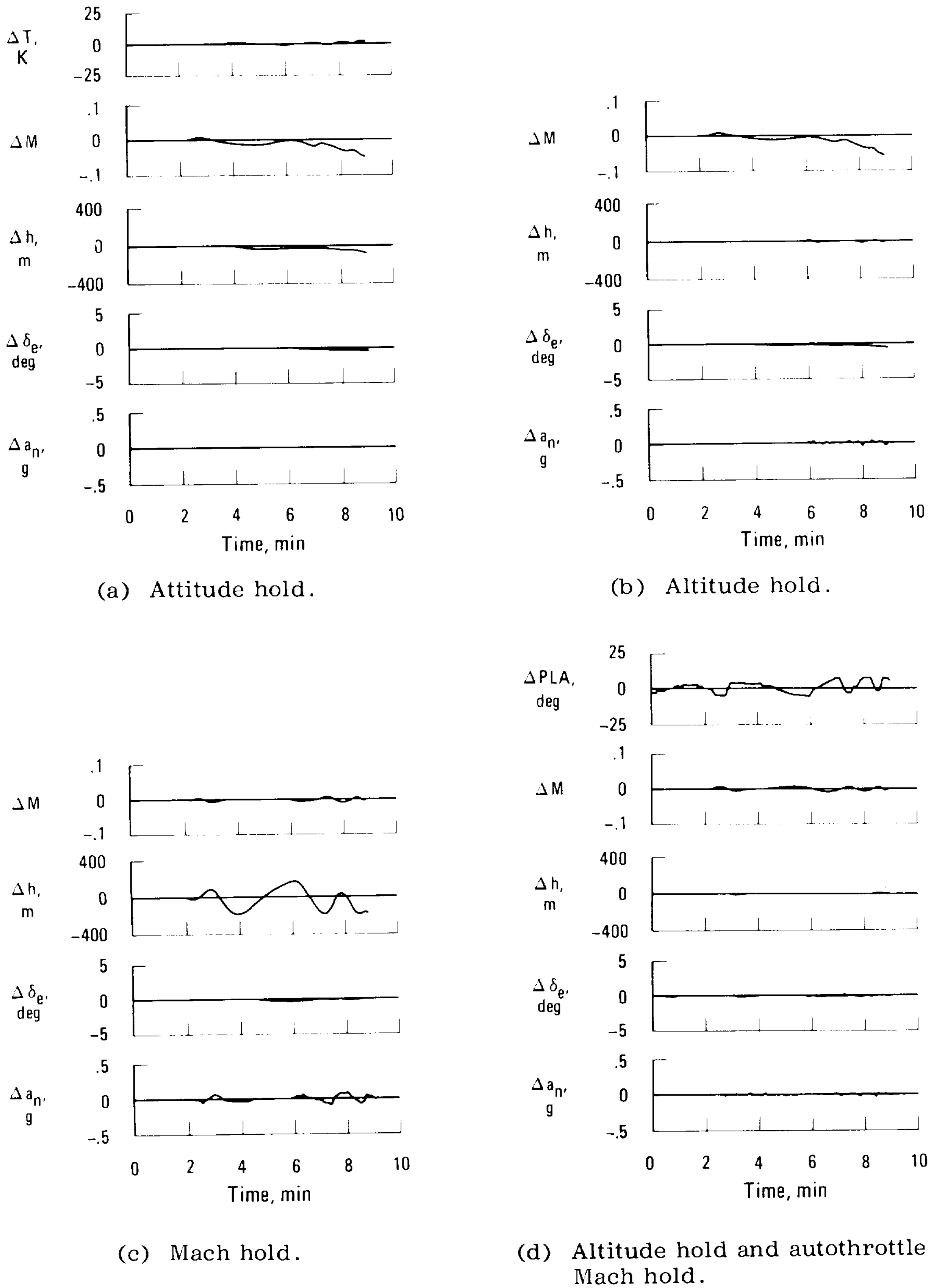


Figure 13.—YF-12 autothrottle control system.



(a) Attitude hold.

(b) Altitude hold.

(c) Mach hold.

(d) Altitude hold and autothrottle Mach hold.

Figure 14.—Simulated aircraft response to nominal temperature variations with different types of control. $M \approx 3.0$.

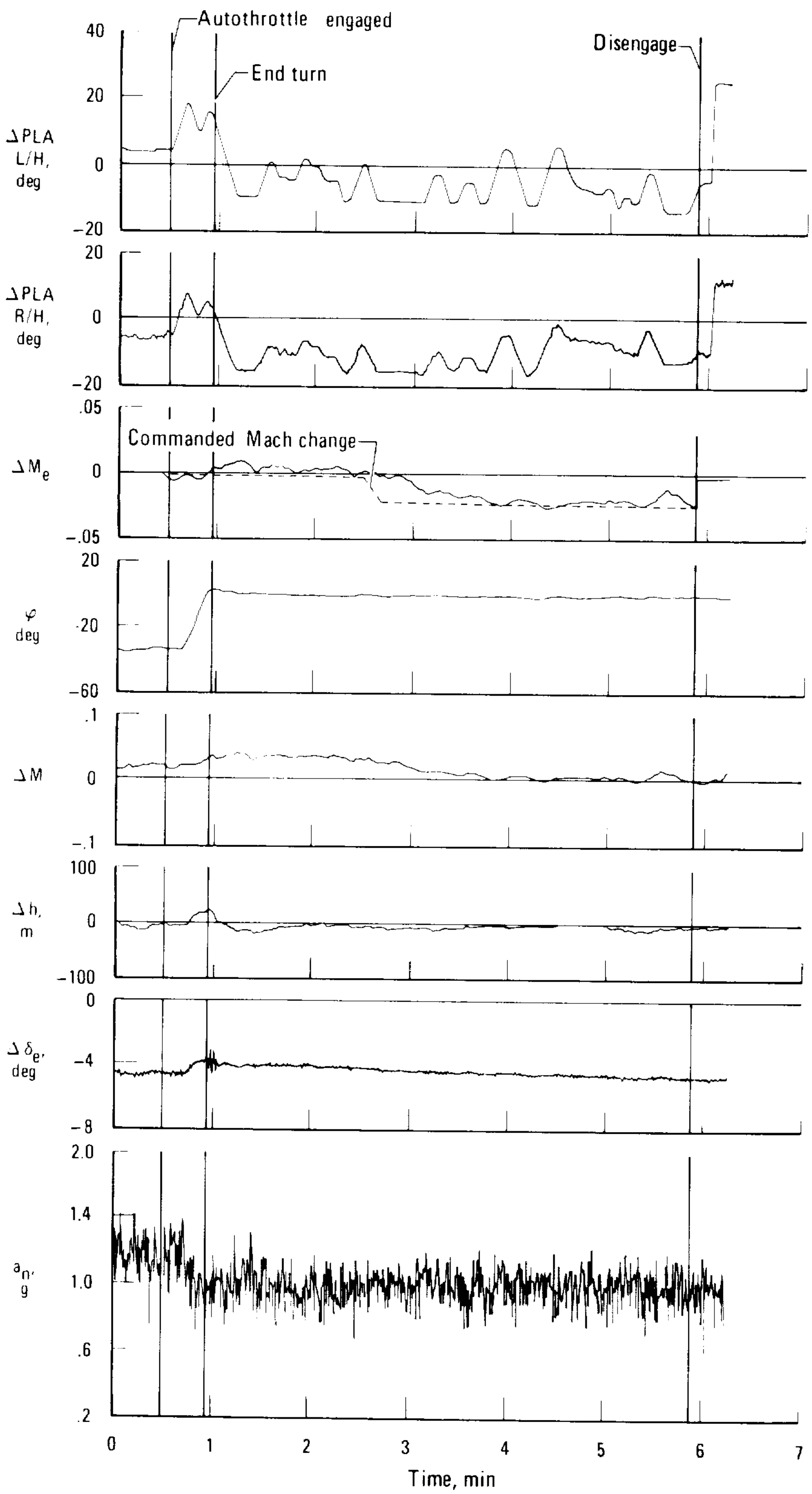


Figure 15.—Autothrottle Mach hold and altitude hold. $M \approx 3.0$, $h \approx 22{,}100$ m.

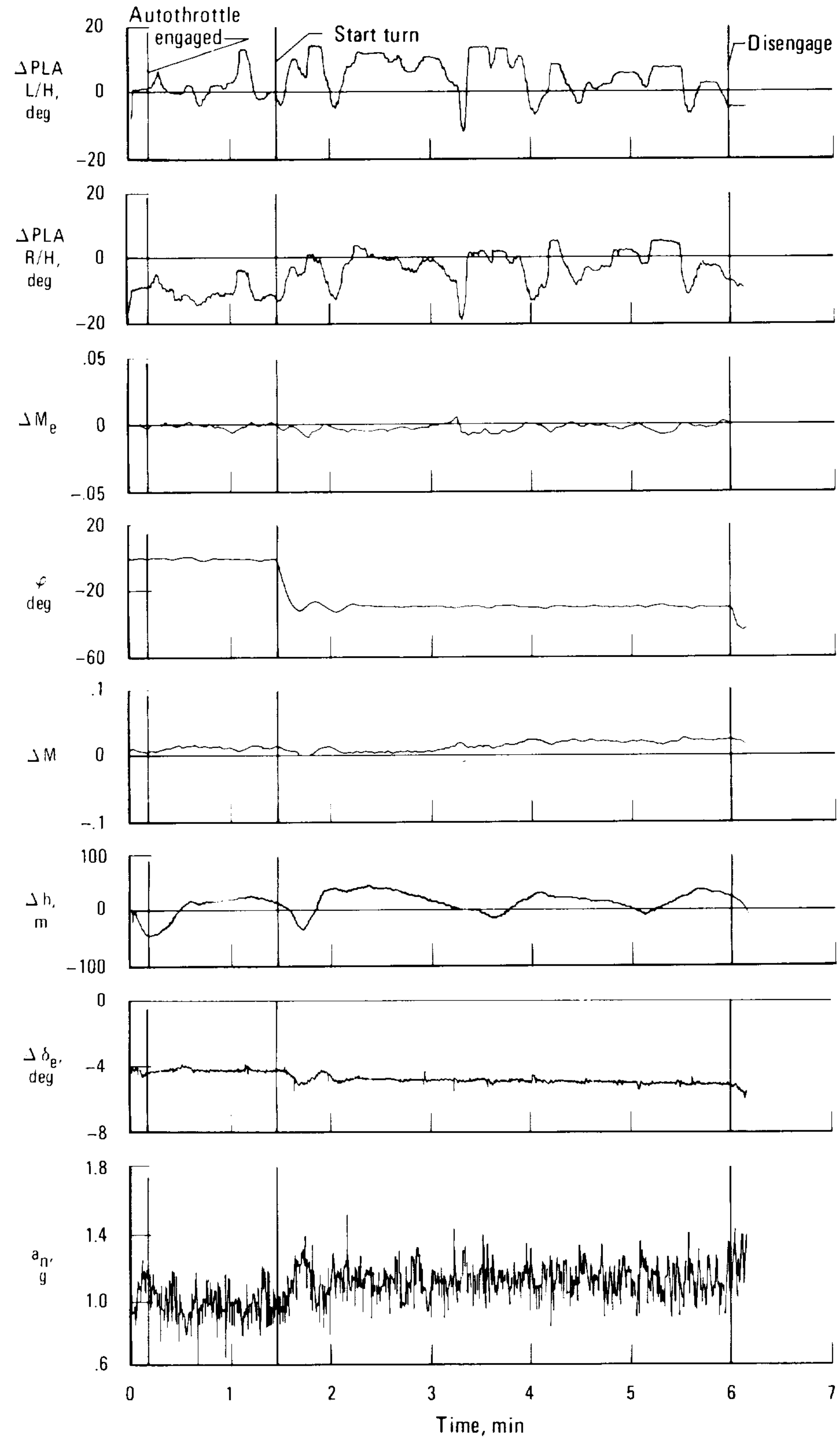


Figure 16.—Autothrottle Mach hold and altitude hold. $M \approx 2.8$, $h \approx 21{,}030$ m.