

1 N 77 - 18089

A REVIEW OF SUPERSONIC CRUISE FLIGHT PATH CONTROL

EXPERIENCE WITH THE YF-12 AIRCRAFT

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SUMMARY

Flight research with the YF-12 aircraft indicates that solutions to many handling qualities problems of supersonic cruise are at hand. Airframe/propulsion system interactions in the Dutch roll mode can be alleviated by the use of passive filters or additional feedback loops in the propulsion and flight control systems. Mach and altitude excursions due to atmospheric temperature fluctuations can be minimized by the use of a cruise autothrottle. Autopilot instabilities in the altitude hold mode have been traced to angle of attack-sensitive static ports on the compensated nose boom. For the YF-12, the feedback of high-passed pitch rate to the autopilot resolves this problem. Manual flight path control is significantly improved by the use of an inertial rate of climb display in the cockpit.

INTRODUCTION

At the 1971 operating problems conference (ref. 1), some handling qualities problems of high altitude, supersonic cruise aircraft were discussed. An area of primary concern was longitudinal and lateral-directional flight path control. Longitudinal flight path control problems manifest themselves as altitude or Mach excursions, or both, that occur in an apparently random and unpredictable manner. These incidents have a history beginning with the XB-70 aircraft and extending to the YF-12 aircraft (ref. 1) and, more recently, the Concorde aircraft (ref. 2). Lateral-directional control problems of the YF-12 aircraft (ref. 3) manifest themselves as large forces and moments induced by inlet spike and bypass door movements and reductions in Dutch roll damping due to automatic inlet operation.

Since the last operating problems conference, research pertinent to supersonic cruise aircraft has been relatively low key. Nevertheless, significant progress has been made and solutions to several problems are at hand. Several papers and reports (refs. 3 to 7) have explored the primary areas of concern, such as airframe/propulsion system interactions, atmospheric disturbances, autopilot performance, and pilot displays.

This paper will review the high speed, high altitude flight path control problems discussed five years ago and the developments in these areas with the YF-12 aircraft since then. This study is neither final nor complete: more operating experience is required to confirm the adequacy of the solutions and to investigate additional problems.

SYMBOLS

Physical quantities are given in the International System of Units (SI) and parenthetically in U.S. Customary Units. All measurements except temperature were taken in Customary Units.

a_n	normal acceleration, g
C_x	longitudinal force coefficient
Δh	incremental altitude, m (ft)
L	normalized rolling moment, $1/\text{sec}^2$
M	Mach number
N	normalized yawing moment, $1/\text{sec}^2$
Δp_s	static pressure error, N/m^2 (lb/ft^2)
α	angle of attack with respect to wing reference plane, deg
β	angle of sideslip, deg
β_i	indicated angle of sideslip, deg
δ_a	differential elevon deflection, deg
δ_e	average elevon deflection, deg
δ_r	rudder deflection, deg
ζ_{DR}	Dutch roll damping ratio
$\zeta\omega_{n_{SP}}$	short period damping factor, rad/sec
η	differential bypass door opening, right bypass door position minus left bypass door position, percent
τ_β	sideslip sensor lag, sec
$\omega_{n_{SP}}$	short period frequency, rad/sec

Subscripts:

$M, \beta, \delta_a, \delta_r, \eta$ partial derivative with respect to subscripted variable

AIRFRAME/PROPULSION SYSTEM INTERACTIONS

Because airframe/propulsion system interactions are probably the most important factor in supersonic aircraft flight path control, this topic will be discussed first.

The demands of efficient cruise above Mach 2.0 has led to the use of variable geometry and mixed-compression inlets. A simplified schematic of a variable geometry inlet and control system is shown in figure 1. This inlet is representative of that used in the YF-12 aircraft. The inlet has a translating spike and forward bypass doors to control the position of the normal shock in the inlet. If the normal shock is positioned too far to the rear of the inlet, losses in efficiency and, thus, range will occur. If the normal shock is too far forward, it can become unstable and be expelled from the inlet (unstart), which causes large thrust losses and airflow disturbances. The desired operating position of the normal shock is a function of Mach number, angle of attack, and angle of sideslip. The inlet can be automatically controlled by a computer that varies the spike and bypass door positions as functions of these critical variables.

Dutch Roll Interactions

The propulsion system can exert a strong influence on the aircraft's stability and control characteristics. An example of a lateral-directional airframe/propulsion system interaction (ref. 3) is shown in figure 2. The airplane's response to a rudder pulse is illustrated with the inlets fixed and with the inlets operating automatically. The stability augmentation system is off. When the inlets are operating automatically, the Dutch roll motion is divergent. Because the Dutch roll motion has a relatively short period, the Mach number is constant and the only significant inlet control variable is the angle of sideslip. To compensate for local flow effects, the bypass doors on the windward side open farther with the sensed angle of sideslip than the doors on the leeward side. This causes asymmetric motion of the bypass doors with the net result that the differential bypass door deflection is in phase with the angle of sideslip. The spikes move in a similar manner. The analysis of these time histories (ref. 3) shows that the observed motions are due to the magnitude of the forces and moments produced by automatic inlet operation, the effect of those forces and moments on the aircraft's stability and control, and a 0.5-second lag (at this flight condition) in the sideslip sensor used by the inlet computer. These factors will be discussed in the following paragraphs.

Table 1 compares the effectiveness of the bypass doors in producing rolling and yawing moments to that of the aerodynamic control surfaces. Airplane control effectiveness is expressed in terms of percent of full deflection, rather than degrees of rudder or aileron. This provides a common base for comparison with the bypass

door effectiveness, which is expressed in terms of percent of full bypass door opening. In the normal operating range, the bypass doors have the same order of magnitude of effectiveness as the rudder and ailerons: in other words, 10 percent aileron deflection has approximately the same effect as 10 percent bypass door deflection. Fortunately, other YF-12 data indicate that due to choking, the effectiveness of the bypass doors as moment producers decreases considerably as the doors open beyond the normal operating position. If this effectiveness did not decrease, full bypass door openings could overpower the aerodynamic controls. (To simplify the analysis, the bypass door and spike effects have been combined, which is valid at this flight condition because the spikes move in phase with the bypass doors. In addition, investigations indicate that at this flight condition the bypass doors are more effective than the spikes.)

Table 2 shows the effect of the inlet on the static lateral-directional stability of the airplane. The bypass doors are programmed by the inlet computer such that a bypass door opening of approximately 3 percent is commanded for each degree of sideslip. Thus, the moments generated by automatic inlet operation are coupled to sideslip. The table gives the static directional stability parameter (N_β) and the dihedral effect parameter (L_β) for the basic aircraft (inlets fixed) and for automatic inlet operation. The yawing moments produced by static stability are in the same sense as those produced by the bypass doors (N_η). Thus, these effects are additive and directional stability is improved 40 percent by automatic inlet operation. However, the rolling moments produced by the bypass doors oppose the rolling moments due to dihedral effect and the net result is a change in sign of the effective L_β .

The influence of automatic inlet operation on the Dutch roll damping is primarily determined by the lag in the sideslip sensor for the inlet computer, which acts in conjunction with the yawing moments induced by the bypass doors. Figure 3 illustrates the influence of the sideslip sensor lag on the Dutch roll damping ratio for a nominal value of yawing moment due to bypass door deflection for the YF-12 aircraft. The figure shows that lags cause the damping of the Dutch roll mode to become unstable. However, it is relatively easy to eliminate the lag or, possibly, provide a lead. When a lead is provided, the airframe/propulsion system interaction could be used to enhance aircraft damping. Feasibility studies indicate that Dutch roll damping can be improved by the use of passive filters or feedback loops such as the feedback of a yaw rate signal to the bypass doors.

Phugoid Interactions

Damping changes due to automatic inlet operation have also been documented for the phugoid mode. Figure 4 illustrates a typical phugoid motion of the YF-12 aircraft for fixed and automatic inlet operation. In both cases the aircraft was initially disturbed by the pilot's opening and closing the bypass doors, which momentarily increases drag and decreases thrust.

An unpublished analysis of YF-12 phugoid data indicates that the primary influence is on C_{xM} , the change in longitudinal force coefficient (thrust minus drag) with respect to Mach number (table 3). For a typical subsonic jet aircraft at a constant throttle setting, drag tends to increase faster with speed than thrust, which increases phugoid damping. For high performance supersonic propulsion systems, however, efficiency increases with Mach number and, at a constant altitude, thrust can actually increase faster than drag. Conversely, when the aircraft decelerates, thrust can decrease faster than drag. Because automatic inlet operation is more efficient than fixed inlet operation, this effect is accentuated, as illustrated by the change in C_{xM} in table 3.

It is not certain whether these changes in phugoid damping contribute to piloting difficulties. In any case, the basic phenomena are understood and can be suppressed with an autopilot or a stability augmentation system if necessary.

LONGITUDINAL FLIGHT PATH CONTROL

Many factors are involved in the long history of incidents of altitude and Mach number excursions with supersonic cruise aircraft. Some primary factors are autopilot behavior in the presence of atmospheric temperature fluctuations, system characteristics such as lags and angle of attack sensitivity, and inadequate pilot displays.

Mach Hold Autopilot Behavior

Manual control of Mach number and altitude can involve a sizable pilot workload when conditions are not ideal. In addition, the pilot must monitor a variety of aircraft systems (particularly the propulsion system) and contend with a rapid succession of air traffic control checkpoints because of the high cruise speed. Consequently, autopilot operation is essential for pilot relief.

However, some conventional autopilot modes respond unfavorably to atmospheric temperature changes. For example, a conventional Mach hold autopilot uses elevons to maintain Mach number. Basically, it attempts to trade altitude for speed. At high speeds, however, large changes in altitude are required to obtain relatively small changes in speed. When atmospheric temperature changes are encountered, the autopilot interprets these as instantaneous Mach number changes and induces large altitude changes to attempt to compensate. This is illustrated in figure 5, in which the solid line shows the simulated response of a YF-12 aircraft to a 4° C (7.2° F) step change in temperature.

Unpublished studies show that a cruise autothrottle alleviates this problem by providing an additional controller which permits control of Mach number independent of altitude. The dashed line in figure 5 shows a simulator response with the autothrottle system. A cruise autothrottle was recently installed in the YF-12

aircraft and flight tests are in progress to verify these studies in an operational environment. Similar experiences with the Concorde aircraft have also led to the conclusion that a cruise autothrottle is needed (ref. 8).

Altitude Hold Autopilot Behavior

Difficulties have also been encountered with conventional altitude hold modes, and YF-12 experience (ref. 6) indicates that these cases can be quite subtle and complex. The YF-12 problems appear to be extremely random and unpredictable: sometimes the problems are associated with obvious atmospheric temperature fluctuations and sometimes they are not. The altitude hold mode on the YF-12 aircraft was designed for use below 18,288 meters (60,000 feet), but because nothing in the design precluded its use above that altitude, it was decided to investigate the behavior of the altitude hold autopilot at high altitudes. The results appear to be inconsistent in that on some occasions the altitude hold autopilot maintained altitude within ± 30.5 meters (± 100 feet), whereas on other occasions large altitude excursions or bursts of short period instability occurred. Figure 6 shows an example of acceptable altitude hold performance (ref. 6) and figure 7 shows an example of unacceptable performance. In figure 7, note the bursts of divergent-convergent short period oscillations, the rough ride (as indicated by the normal acceleration time history), and the poor altitude hold performance.

Analysis and simulation studies showed that adjustment of the autopilot gains could improve the long period altitude hold performance, but the short period instabilities persisted and were traced to the angle of attack sensitivity of the static ports on the compensated nose boom of the YF-12 aircraft. The compensated nose booms are used to minimize airspeed errors in the transonic speed range; unfortunately, these nose booms tend to be sensitive to angle of attack.

The nature of the angle of attack sensitivity of the nose boom is illustrated in figure 8. As angle of attack increases, the slope ($\Delta p_s / \Delta \alpha$) of the curve of static pressure error versus angle of attack increases. Analysis has shown that $\Delta p_s / \Delta \alpha$ has a direct effect on short period stability. This is illustrated in figure 9, which is a root locus of the airplane and autopilot for various values of $\Delta p_s / \Delta \alpha$. As $\Delta p_s / \Delta \alpha$ becomes more negative, the short period mode becomes unstable.

Therefore, relatively small changes in angle of attack can cause marked changes in system stability. On days when the atmosphere is smooth and the aircraft precisely trimmed, good autopilot behavior is possible. On the other hand, any roughness in the atmosphere that would induce more autopilot activity and larger angle of attack excursions would lead to instability. Figure 7 shows that the oscillations diverge when angle of attack increases and converge when angle of attack decreases.

Simulation studies showed that the angle of attack sensitivity could be counteracted by adding a high-passed pitch rate signal to the autopilot. The addition of high-passed pitch rate increased the damping of the aircraft-autopilot system without interacting with other modes, so that the system was insensitive to the effects of angle of attack. The angle of attack sensitivity could also be counteracted by the

computation of a correction in the air data computer or the relocation of the static ports to a location that is insensitive to angle of attack. The use of the high-passed pitch rate feedback, however, is advantageous in that it does not require as precise a prior knowledge of the angle of attack induced errors or nose boom characteristics.

To verify these results in the flight environment, the YF-12 altitude hold autopilot mode was modified with gains optimized for higher altitudes and a high-passed pitch rate feedback signal to compensate for the angle of attack-sensitive nose boom. The performance of the modified altitude hold autopilot is illustrated in figure 10. Although the atmosphere appears to be smooth, the angle of attack range is similar to the example of figure 7, where short period instabilities occurred. In this case, however, autopilot performance is smooth with no signs of short period instability.

Manual Flight Path Control

To assist the pilot in manual flight path control tasks, an inertial rate of climb display was provided in the YF-12 cockpit (ref. 7). Vertical velocity information from the onboard inertial guidance system was used to drive a horizontal needle on the attitude/director indicator. This display circumvents the lag in the air data system and the errors due to the angle of attack sensitivity of the nose boom.

Pilots' comments on this display were highly favorable. Typical comments were: "immediately obvious this is a lot better", "a big help", "very helpful", and "nice for level accelerations." A limited semiquantitative evaluation of the display was made, and the results, which are summarized in table 4, show an average improvement in pilot rating of approximately 2 1/2 on the Cooper-Harper scale—a significant improvement.

CONCLUDING REMARKS

Solutions to several of the handling qualities problems of supersonic cruise vehicles discussed at the 1971 operating problems conference are at hand. However, more operating experience is needed to confirm the adequacy of these solutions and to investigate additional problems. The primary problems addressed in 1971 and the solutions developed with the YF-12 aircraft since then are summarized as follows:

Airframe/propulsion system interactions are caused by significant forces and moments on the airframe induced by bypass door and spike operation. For the Dutch roll mode, these forces and moments are coupled to the aircraft's responses by the inlet computer that controls the spike and bypass door positions as a function of angle of sideslip. This coupling is adversely affected by lags in the sideslip sensor. These adverse interactions can be reduced or made favorable by the use of passive filters or additional feedback loops in the propulsion or flight control system, or both.

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Atmospheric temperature fluctuations can cause a conventional Mach hold autopilot to induce large Mach and altitude excursions. The use of a cruise autothrottle for Mach control alleviates this problem.

Instabilities in the altitude hold autopilot systems have been traced to the angle of attack sensitivity of the static ports on the compensated nose boom. For the YF-12 aircraft, the feedback of high-passed pitch rate to the autopilot resolves this problem.

Manual flight path control is significantly improved by the use of an inertial rate of climb display in the cockpit.

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TABLE 1.—COMPARISON OF BYPASS DOOR AND CONTROL EFFECTIVENESS

$$L_{\eta} = 0.35 \text{ deg/sec}^2\text{-percent}$$

$$L_{\delta_a} = 0.30 \text{ deg/sec}^2\text{-percent}$$

$$N_{\eta} = 0.11 \text{ deg/sec}^2\text{-percent}$$

$$N_{\delta_r} = -0.073 \text{ deg/sec}^2\text{-percent}$$

TABLE 2.—INFLUENCE OF AUTOMATIC INLET OPERATION ON EFFECTIVE AIRCRAFT STATIC STABILITY

Inlet operation	Effective stability derivative	
	L_{β} , 1/sec ²	N_{β} , 1/sec ²
Fixed	-0.90	0.86
Automatic	0.24	1.23

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TABLE 3.—EFFECT OF INLET OPERATION ON C_{x_M}

Inlet operation	C_{x_M}
Fixed	-0.028
Automatic	0.025

TABLE 4.—PILOT RATINGS OF ALTITUDE CONTROL

$M \approx 3.0$

Task	Cooper-Harper rating	
	Without inertial rate of climb display	With inertial rate of climb display
Transition from climb to level flight	6	3
Stabilization after pitch disturbance	5	3
Descent	5	3

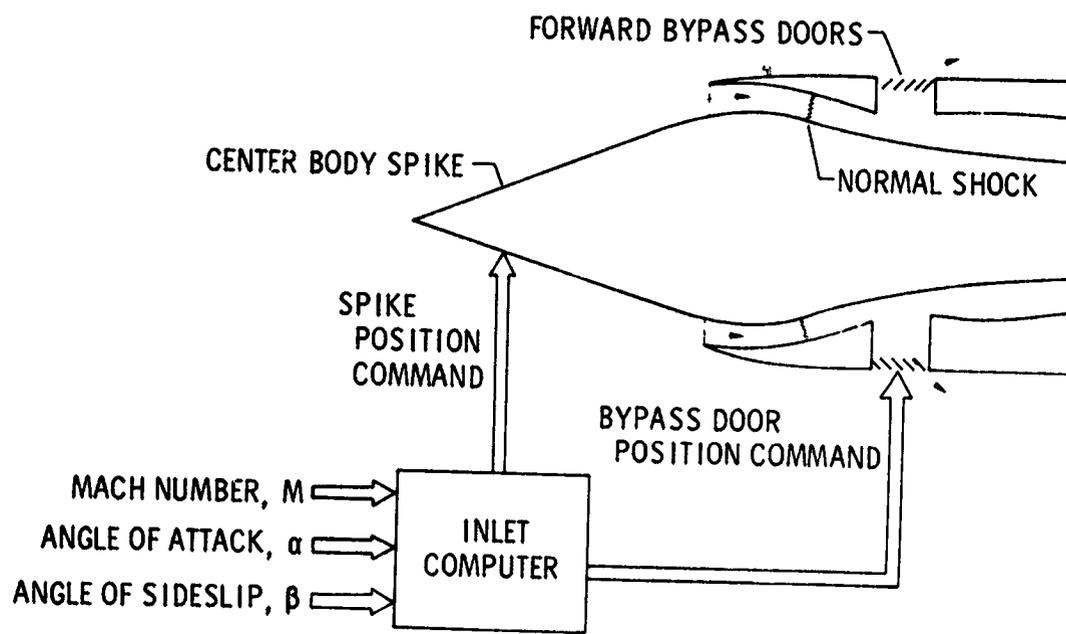
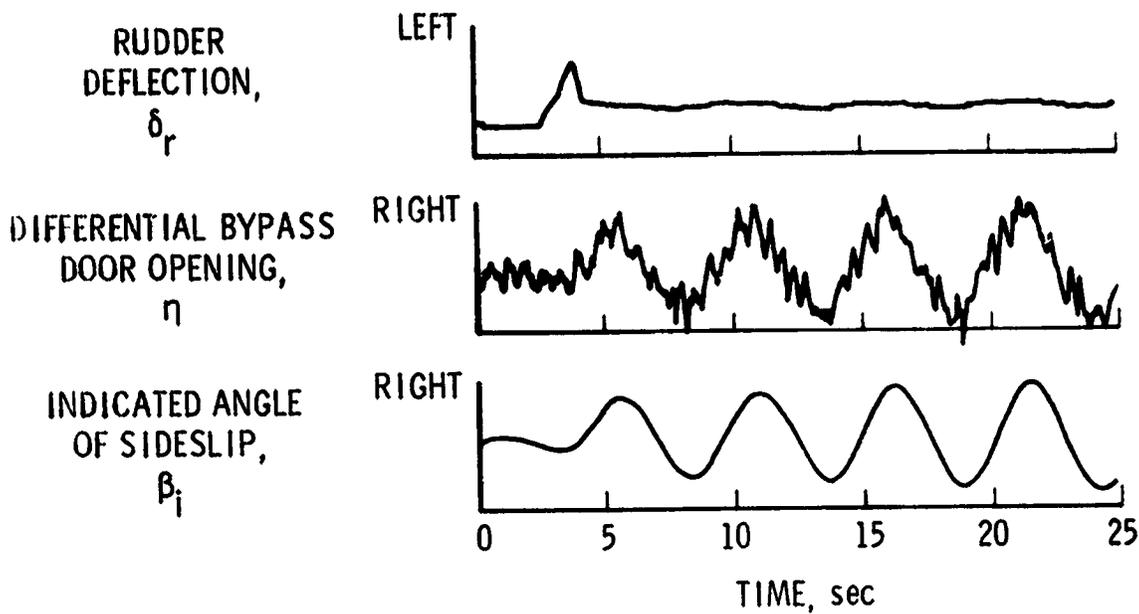
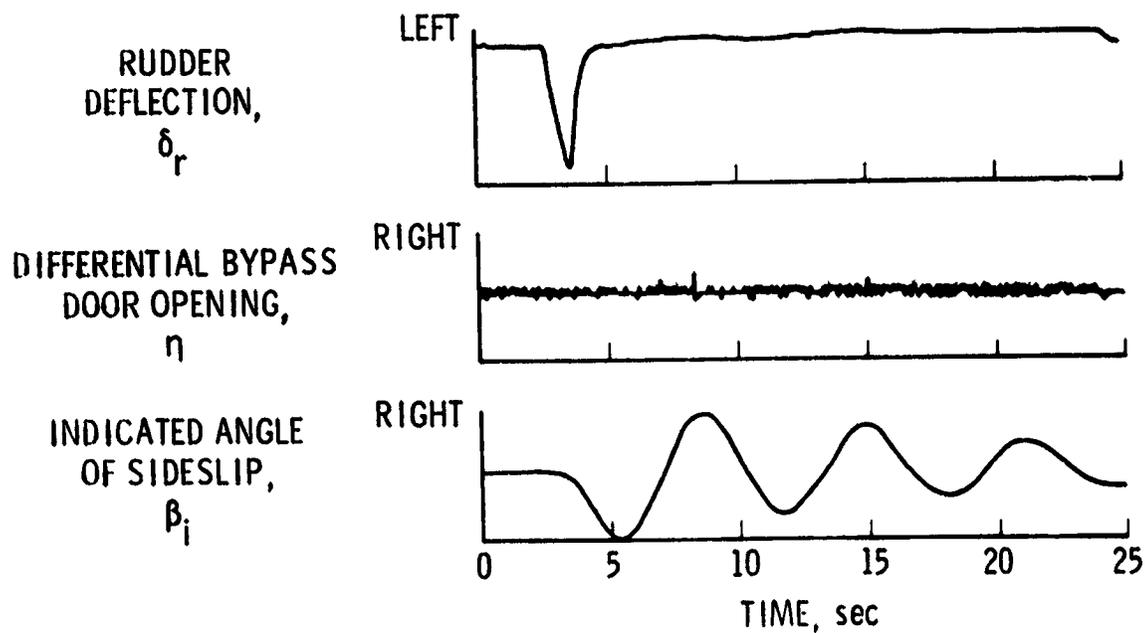


Figure 1.- Simplified schematic of variable geometry inlet and control system.



(a) Inlets automatic.



(b) Inlets fixed.

Figure 2.- Dutch roll response to rudder pulse. Yaw stability augmentation system off, $M \approx 3.0$.

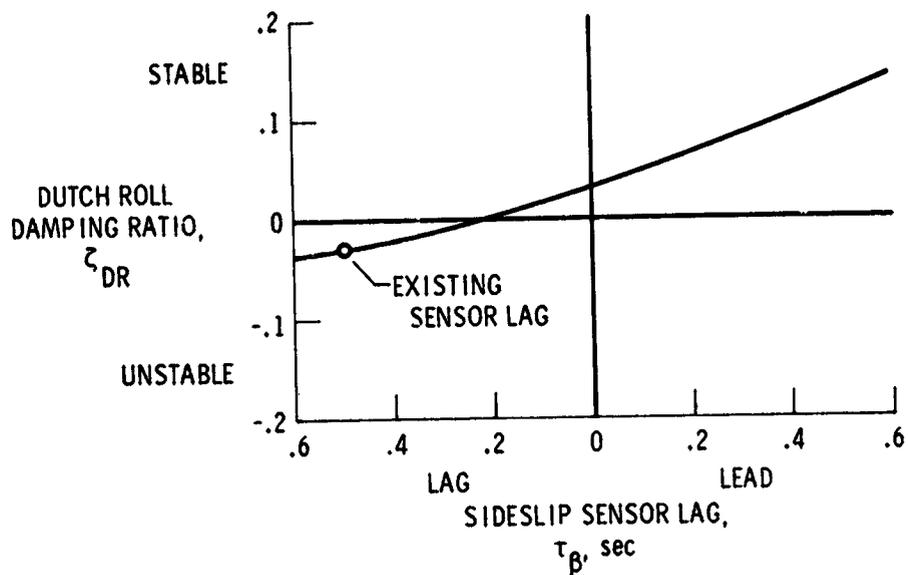


Figure 3.- Influence of sideslip sensor lag or lead compensation on Dutch roll damping ratio.

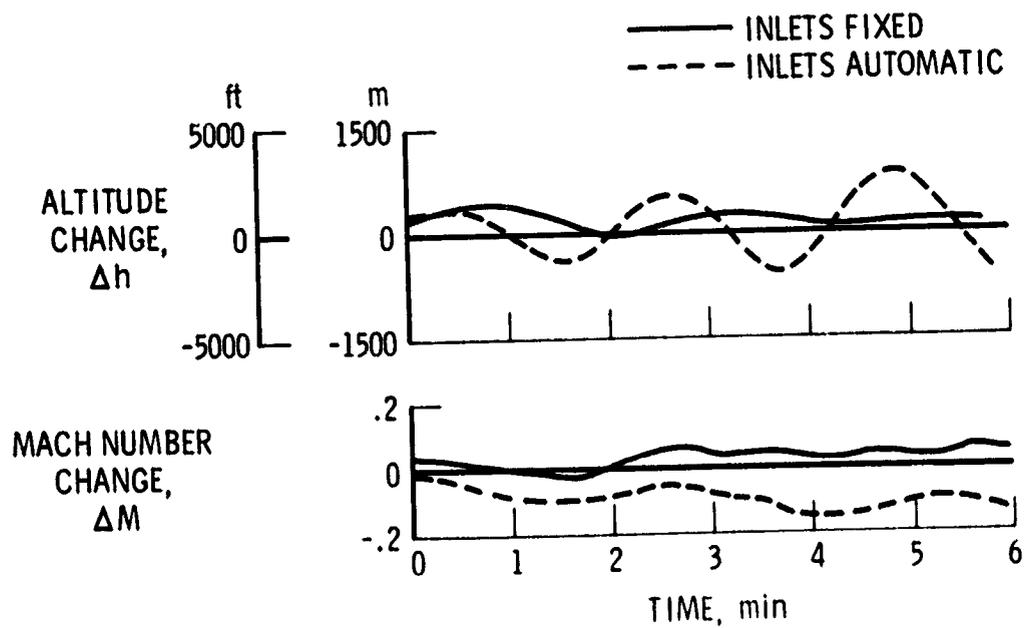


Figure 4.- Effect of inlet operation on YF-12 phugoid response.

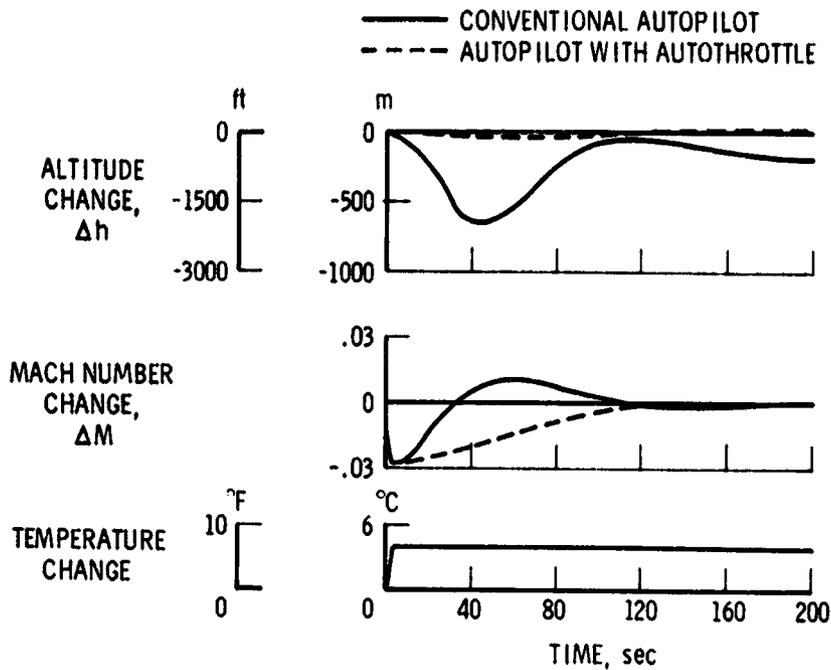


Figure 5.- Simulated response of YF-12 Mach hold autopilot.

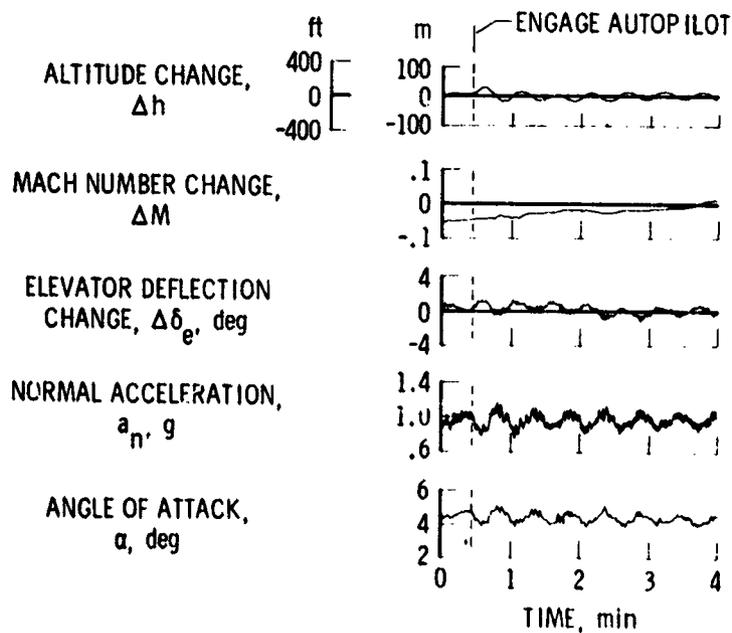


Figure 6.- Acceptable altitude hold. Stable atmosphere; $M \approx 3$; $h \approx 23,622$ m (77,500 ft).

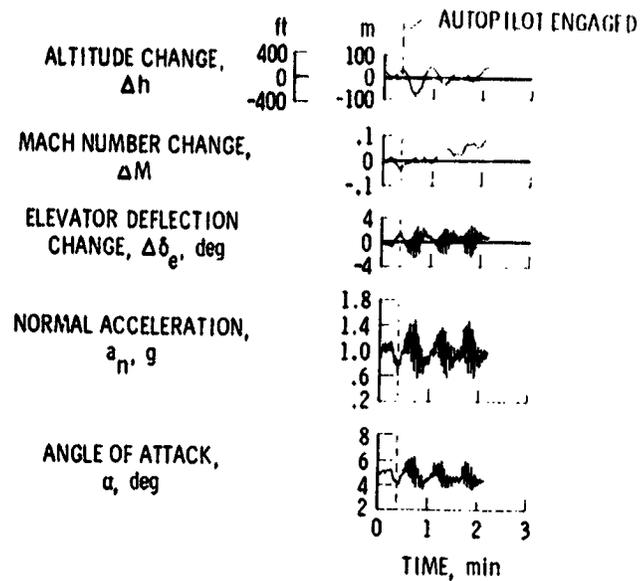


Figure 7.- Unacceptable altitude hold.
 Unstable atmosphere; $M \approx 3$;
 $h \approx 23,622$ m (77,500 ft).

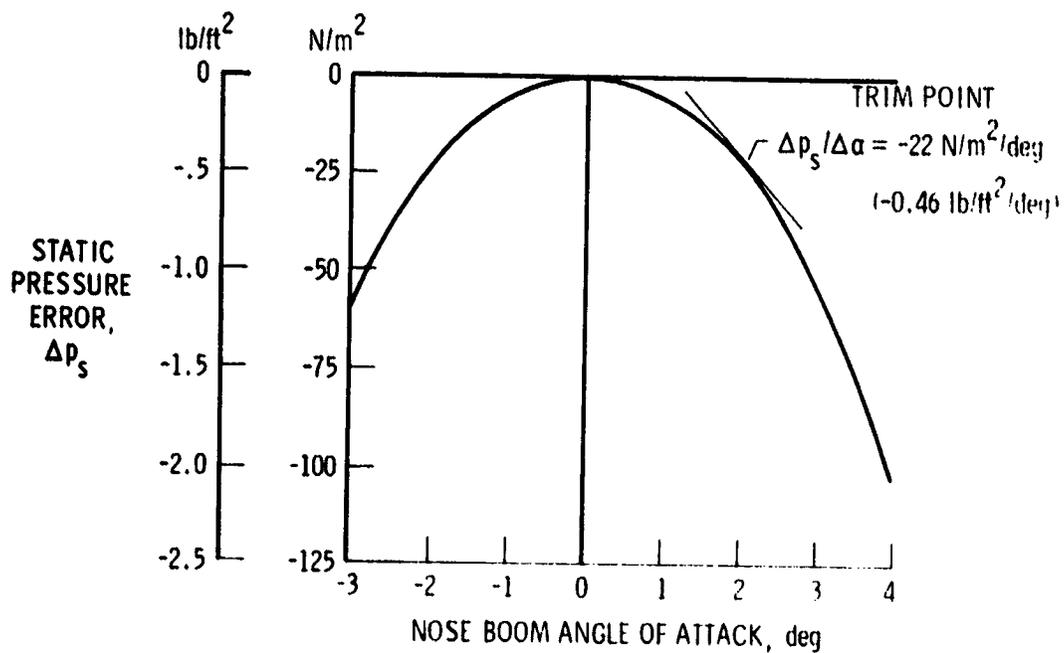


Figure 8.- Variation of static pressure error with nose boom angle of attack.

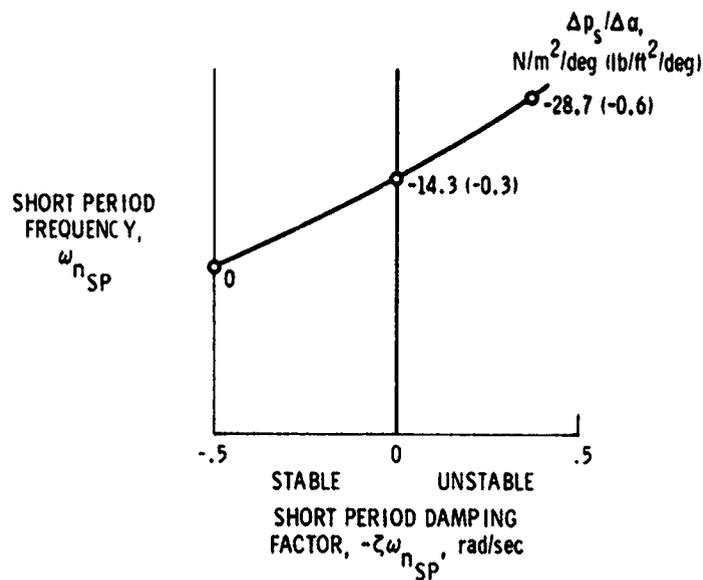


Figure 9.- Variation of short period roots with $\Delta p_s / \Delta \alpha$ for altitude hold mode.

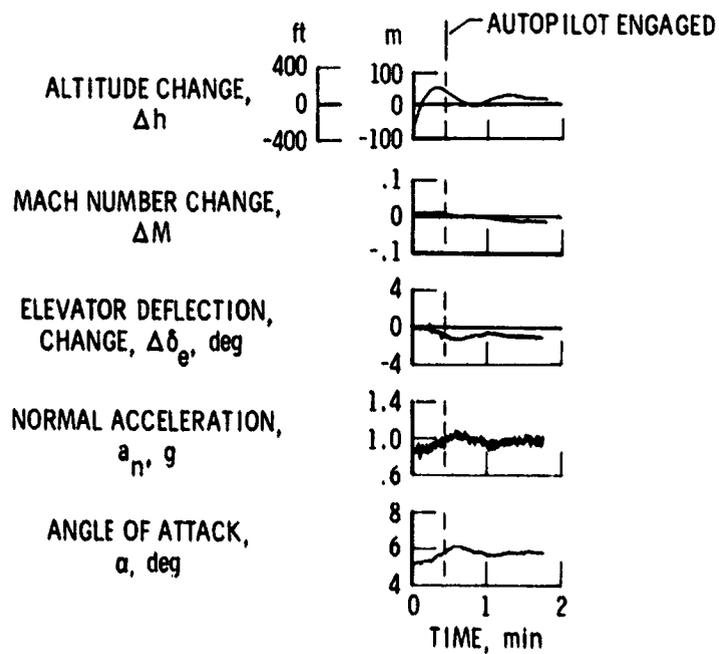


Figure 10.- Performance of modified altitude hold autopilot.