HANDLING QUALITIES ASPECTS OF NASA YF-12 FLIGHT EXPERIENCE

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SUMMARY

This paper reviews the handling qualities of the YF-12 airplane as observed during NASA research flights over the past five years. Aircraft behavior during takeoff, acceleration, climb, cruise, descent, and landing are discussed. Pilot comments on the various flight phases and tasks are presented. Handling qualities parameters such as period, damping, amplitude ratios, roll-yaw coupling, and flight path response sensitivity are compared to existing and proposed handling qualities criteria. The influence of the propulsion systems, stability augmentation, autopilot systems, atmospheric gusts, and temperature changes are also discussed. The results indicate that YF-12 experience correlates well with flying qualities criteria, except for longitudinal short period damping, where existing and proposed criteria appear to be more stringent than necessary. Problems with long period flight path control and inlet unstarts are generic to supersonic cruise vehicles, and criteria for these characteristics do not exist. The influence of the propulsion system must be considered when evaluating vehicle stability and control.

INTRODUCTION

The YF-12 airplane is the only true Mach 3 cruise aircraft in the free world, and, as the record books attest, aircraft of the YF-12 series are the fastest in the world. Although designated a fighter, the aircraft was designed for missile-launching interceptor and high-altitude reconnaissance roles. Consequently, its design emphasizes range and speed, rather than maneuverability. Flight research programs with this aircraft have offered NASA a unique opportunity to observe the handling qualities of a supersonic cruise vehicle in an actual flight environment.

This paper discusses aspects of YF-12 handling qualities that appear to have general applicability to supersonic cruise vehicles, with particular emphasis on operating problems and handling qualities criteria. A qualitative description of the aircraft's flying qualities throughout the flight envelope is presented in terms of pilot comments. Since the aircraft is normally operated with a full-time stability augmentation system (SAS), this paper primarily discusses the augmented aircraft. However, some SAS-off cases of special interest are also covered. The latter part of the paper presents a detailed and quantitative description of certain selected characteristics. Correlations with handling qualities criteria are made where applicable. Finally, the implications of this experience are discussed in terms of potential requirements for future supersonic cruise vehicles.

SYMBOLS

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

a_t	lateral acceleration at aircraft center of gravity, g
a_x	longitudinal acceleration at aircraft center of gravity, g
Δh	incremental altitude, m (ft)
M	Mach number
n/α	change in normal acceleration per unit change in angle of attack, g/rad
p	roll rate, deg/sec
r	yaw rate, deg/sec
β	angle of sideslip, deg
δ_a	differential elevon deflection, percent of maximum
δ_r	rudder deflection, percent of maximum
ζ_{DR}	Dutch roll damping ratio
ζ_{SP}	longitudinal short period damping ratio
$\frac{\dot{\theta}}{\dot{\theta}_{ss}}$	ratio of peak pitch rate to steady state pitch rate
τ_r	roll mode time constant, sec
τ_s	spiral mode time constant, sec

φ bank angle, deg

$\omega_{n_{DR}}$ Dutch roll undamped natural frequency, rad/sec

$\omega_{n_{SP}}$ longitudinal short period undamped natural frequency, rad/sec

ω_{φ} frequency term of bank angle-to-aileron transfer function numerator, rad/sec

AIRPLANE DESCRIPTION

The YF-12 airplane is an advanced, twin-engined, delta-winged interceptor designed for long-range cruise at speeds greater than Mach 3 and at altitudes above 24,384 meters (80,000 feet). A photograph and a three-view drawing of the airplane are shown in figures 1 and 2, respectively. The airplane has two axisymmetric, variable-geometry, mixed-compression inlets, which supply air to two J58 engines. Each inlet has a translating compression 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 maintain the normal shock in the optimum position. Manual control of the spike and bypass doors is also available, which enables the pilot to fix the spike and bypass doors at a desired position.

Two nacelle-mounted, all-movable vertical tails provide directional stability and control. Additional directional stability is provided by ventral fins on the nacelles and fuselage. Each vertical tail is canted inward and pivots on a small stub section attached directly to the top of each 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 a stability augmentation system (SAS) engaged to provide artificial stability in pitch and yaw, and damping in pitch, yaw, and roll. An autopilot with pitch attitude, knots equivalent airspeed (KEAS), Mach, and altitude hold modes is also available. Additional details on the flight and propulsion controls can be found in references 1 to 3.

QUALITATIVE DESCRIPTION OF AIRCRAFT FLYING QUALITIES

When test pilots discuss aircraft handling qualities, they are more likely to concentrate on the poor characteristics and not mention the good points. In this paper both the desirable and undesirable handling qualities of the YF-12 aircraft are discussed to give a complete picture of a very impressive high-speed, high-altitude aircraft. In addition to the basic handling qualities, such as damping, force gradients, and control responses, other important areas, such as pilot visibility, structural modes, inertias, and aircraft systems, are discussed.

The pilot commentary presented here is a product of five years of flight experience during the NASA YF-12 flight research program. In this program, the U.S. Air Force YF-12A and YF-12C aircraft are used as test vehicles to gather flight data on aerodynamic loads, propulsion system characteristics, and other areas unique to the environment at speeds in excess of Mach 3.0 and altitudes above 24,384 meters (80,000 feet). The sequence followed in the discussion is that of a normal test flight from takeoff to landing.

Takeoff and Initial Climb

Takeoff is begun with afterburner power and takeoff acceleration is normally good. Back stick force is applied at approximately 160 knots indicated airspeed (KIAS) and the nose wheel lifts off at approximately 180 KIAS. The aircraft is then rotated and held at a 10° pitch attitude while it accelerates to approximately 200 KIAS where lift-off occurs. The longitudinal control response and damping are good and there is no tendency to overrotate or hunt for the 10° takeoff attitude. However, the aircraft's ride and its response to a rough runway make it difficult at times to smoothly rotate to and hold a given takeoff attitude. At Edwards Air Force Base, both rough and smooth runways are available to help evaluate these characteristics. On a rough runway, the flexible fuselage of the YF-12 aircraft gives the pilot a very bumpy ride in the vertical axis. This physical input to the pilot, in addition to the motion of the aircraft's nose, makes it difficult to hold a precise takeoff attitude. The problem involves a very uncomfortable ride and the possibility of skipping or touching down after initial lift-off. For the pilot, the problem is not considered dangerous, but rather a nuisance; for revenue passengers, the ride may be objectionable.

Gear retraction results in a moderate nose-up trim change that is easily controlled. The pilot must compensate for the trim change to avoid an excessive nose-high attitude after takeoff. Acceleration to 400 KEAS is rapid and the normal procedure is to reduce power to military for the initial climb. Some concentration on speed control is required during the climb. This may be partly due to the loss of the visual horizon as a result of the nose-high climb attitude. In addition, the aircraft's speed stability seems low. Roll and pitch control forces are harmonized and reasonable; responses in these axes are quite adequate. All three axes are well damped with SAS on. Very little rudder activity is required except for trim.

Acceleration and Climb

The subsonic climb is made to approximately 10,700 meters (35,000 feet). Minimum afterburner is selected at 6100 meters (20,000 feet) and maximum afterburner at 7600 meters (25,000 feet). When a speed of Mach 0.9 and an altitude of 10,700 meters (35,000 feet) are attained, a pushover-type acceleration is used to reach supersonic speed. The pushover acceleration is used rather than a level acceleration to expedite the aircraft through the transonic range of high drag into the low supersonic range where more excess thrust is available for the continued acceleration and climb to cruise conditions.

When the supersonic climb KEAS is reached, a constant KEAS (constant dynamic pressure) acceleration climb is made to cruise conditions. Little trim change is required for this particular phase of flight. The aircraft's longitudinal and speed stability is such that the pilot must pay attention to KEAS to avoid overshoots or undershoots in speed. A lack of care with pitch control inputs may result in the pilot's chasing airspeed (making continual corrections to attain the desired airspeed). The autopilot relieves the pilot of the airspeed control task. However, if only the attitude command feature is used on the autopilot, the pilot may still be chasing airspeed through the pitch command wheel. The autopilot KEAS hold mode resolves the problem of airspeed control during the acceleration climb.

A problem that contributes to the pilot's task of maneuvering the aircraft is the delay due to inertia, or the time required to alter the aircraft's vector. Because of this delay, the pilot must anticipate changes and lead the aircraft to arrive at a new speed or altitude without an overshoot. This delay is especially obvious in the establishment of a stabilized point in cruise.

Cruise Flight

As the aircraft approaches the point to level off for cruise, it is operating at design conditions and has excess thrust available. Approximately 1000 meters (3000 feet) below the desired cruise altitude, the pilot must reduce throttle and start the noseover maneuver. Even with anticipation and experience, it is difficult to maneuver precisely to the desired conditions and sometimes several secondary adjustments in speed and altitude are required.

One problem that was discovered early in the program was the excessive lag in the pressure rate of climb indicator. The lag was such that the pilot would often be chasing the pressure rate of climb. This problem was present not only while leveling off, but also during cruise. The addition of an inertial rate of climb display for the pilot's panel greatly improved this situation. The inertial rate of climb display enabled the pilot to control altitude so well that he then became more aware of the inertia in speed response that is associated with the engines, inlets, airspeed, and, in some cases, atmospheric temperature changes. In other words, once the altitude was stabilized by means of the inertial rate of climb information, the pilot noticed it was difficult to set a throttle position that would hold constant speed. This problem was essentially solved by providing the pilot with an inertial longitudinal acceleration display. The addition of an inertial rate of climb display and an inertial longitudinal acceleration display greatly aided the research pilot in setting up the numerous stabilized test points required in the program.

Stability

Stability augmentation system on.—As noted earlier, the longitudinal (speed) stability is such that much effort is required to set up a trim or cruise condition. Once the condition is established, the aircraft with the SAS on will hold speed and altitude well if not disturbed. Unfortunately, small pitch attitude changes not immediately apparent to the pilot occur, and by the time the pilot notices it, a moderate altitude change is underway. In addition, atmospheric changes can cause Mach number changes of ±0.05 without pilot inputs. Therefore, the pilot's constant scanning and full attention are required to hold a precise test condition. The lateral stability appears to be neutral with no tendency for the aircraft to roll off. It is difficult, however, to trim the aircraft with wings exactly level and it is not unusual to have a degree or two of undesired bank angle. Throughout the flight envelope, the directional stability and damping are very high. The aircraft tends to change slightly in directional trim with Mach number change, which may be due to slight differences in engine-inlet performance. Short period damping in all axes is high with the SAS on.

Stability augmentation system off.—Extended flight tests have been conducted with pitch SAS off and with roll and yaw SAS off, but never with pitch and yaw SAS off at the same time. With pitch SAS off, the short period is not as well damped, but the decrease in damping is not immediately apparent to the pilot during cruise conditions with pulse-type inputs. With the yaw and roll SAS off, the reduction in directional damping with increasing Mach number can be observed by the pilot. This reduction is apparent in the case of a rudder-induced sideslip and the slow tendency of the nose to return when the controls are neutralized. In addition, another phenomenon related to the engine-inlet system will actually drive the aircraft into a slowly divergent yaw oscillation with the yaw and roll SAS off. This is caused by the phasing of the automatic inlet response to the sensed sideslip.

Inlet Unstart

The unstart condition of the engine inlets introduces strong pitch, yaw, and roll moments to the aircraft. Depending on the aircraft's attitude at the time of unstart, these inputs can be of some concern to the pilot. The aircraft's response to an unsymmetrical unstart is to roll toward the unstarted inlet and to pitch upward. In level flight with a normal center of gravity and SAS on, the unstart is not of great concern to the pilot; however, the sharp cracking noise, the vibration in the aircraft, and the loss of speed and altitude are disconcerting. The SAS input, in addition to the pilot's natural reaction of forward stick and roll control, normally results in a minimal attitude change. However, if the unstart occurs on the inside engine during a turn or a pullup maneuver, the pilot must respond positively to prevent the divergence of the aircraft's attitude.

The unstart converts a smoothly running, steady aircraft into a noisy, vibrating machine that is rapidly losing altitude and speed. Planned and uplanned unstarts have been experienced with SAS on and SAS off and the pilot's opinion is that it is a much nicer condition with inlets started and SAS on.

Descent

Normal descents are made with inlets started and military power, which results in a long distance being required for descent. No unique handling qualities are present; aircraft handling is similar to that in acceleration and cruise. In an emergency, a more rapid descent can be made by setting the inlets to restart (a high drag condition) to expedite the letdown. Because of the rapid rate of engine cooling, some engine damage could occur in the rapid descent.

Landing

The handling qualities in the landing pattern are very good. The aircraft is well damped and control response is positive. Throttle and thrust response at landing weights is rapid. There is some tendency for the approach speed to vary, which could be due to the high sensitivity of thrust change with throttle movement. The aircraft has a positive ground effect and flare to touchdown is comfortable, usually resulting in smooth landings. A large drag parachute provides braking and nose steering is available for directional control. The military have reported that landings on wet runways with high crosswinds are a problem, but the operation at Edwards has not provided an opportunity to evaluate this condition.

Pilot's Summary

I have had the opportunity to fly a number of high-speed, high-altitude aircraft and, although they all have been fine aircraft, I have been most impressed with the YF-12 aircraft. It is a sophisticated, advanced aircraft that flies in an environment unmatched by other aircraft and does it well. I know that the manufacturer has been lauded numerous times for its accomplishments, but this pilot adds his congratulations for a job well done and still impressive—even today, years after its conception.

QUANTITATIVE DESCRIPTION OF AIRCRAFT HANDLING QUALITIES

The pilot comments in the preceding section are summarized in table I to provide a convenient cross-reference for the more quantitative information contained in this section.

General Characteristics

The pilot comments in the takeoff and landing phase (table I) include a reference to the rough ride on rougher portions of the runway. Figure 3 shows a typical YF-12 response to runway roughness. Peak-to-peak normal accelerations of over 1.0g are experienced. Revenue passengers may object to such a ride, but for military missions it is acceptable.

In the high-speed flight phase, the pilot describes inlet unstarts as a disconcerting experience. An example of the aircraft's response to a typical unstart is given in figure 4 (ref. 4). These time histories illustrate an unstart that occurred at approximately Mach 2.7 with the SAS on and the inlets operating automatically. Within the first second after the unstart, the airplane decelerates 0.2g and experiences a peak lateral acceleration of 0.3g. Obviously, these accelerations would be disturbing to a passenger, and even hazardous if he were not belted in his seat. In addition, the roll rate exceeds 10° per second, and a structural vibration is evident in the directional mode. Although these motions could disturb a passenger, the airplane is considered to be well controlled from the pilot's point of view. However, this control was achieved with the aid of lateral acceleration feedback loops in the SAS and a crosstie system between the inlets, and by limiting the aft center-of-gravity position to maintain relatively high stability levels. Nevertheless, approximately 60 percent of rudder and of aileron was used to control the unstart reactions. No criteria presently exist to evaluate this situation.

Longitudinal Characteristics

Figure 5 summarizes typical YF-12 longitudinal characteristics on the military specification Mil-F-8785B format (ref. 5) for short period natural frequency, $\omega_{n_{SP}}$, and normal acceleration change per unit change in angle of attack, n/α. For the acceleration, climb, and cruise flight phases, n/α varies from 17g to 32g per radian and $\omega_{n_{SP}}$ varies from 2.0 radians per second to 4.6 radians per second with SAS on. With SAS off, the $\omega_{n_{SP}}$ for a high-speed cruise case decreases to 1.6 radians per second. These characteristics are well within the level one boundaries (satisfactory for normal operation), which correlates well with the pilot comments on good longitudinal response, even for the cruise case with SAS off.

Figure 6 summarizes longitudinal short period damping as a function of flight phases with the military specification level one requirements superimposed. SAS-on damping dips below the requirements during the climb, but the pilots still consider the aircraft well damped. Even the SAS-off damping is considered satisfactory by the pilots. This indicates that the military specification requirement may be too stringent for high-altitude climb and cruise flight.

Another criterion of interest is the modified supersonic transport (SST) pitch rate response criterion proposed in reference 6. This criterion is in terms of the time history of the aircraft's response to a step control input. Pure step responses from flight are not available from YF-12 flights, so step responses have been computed using flight verified data for the aerodynamics and control system. In figure 7, typical responses for high-speed cruise are compared to the pitch rate response criterion. The SAS-on case (fig. 7 (a)) meets the criterion fairly well, but the SAS-off cruise case (fig. 7(b)) does not. The pilot comments indicate that this SAS-off cruise case is satisfactory. Although SAS-off experience with the aircraft is quite limited as compared to SAS-on experience, there seems to be a tendency for the pilots to be more tolerant of low damping for high-speed cruise than the criterion would indicate. This SAS-off case also did not correlate with the military specification requirements for damping; however, the military specification is based on a very limited data base (ref. 7).

The pilot comments and aircraft parameters discussed so far are concerned with short term control response, and in general, theses characteristcs are good. However, as table I indicates, Mach and altitude control can be very demanding. This behavior is related to the phugoid and long term control response of the aircraft. Many factors are involved, such as an unfavorable balance of kinetic to potential energy, atmospheric disturbances, low levels of speed stability, low aircraft drag, changes of thrust with Mach number, cockpit displays, and autopilot behavior. It is beyond the scope of this paper to consider these factors in depth, but the following discussion will attempt to provide an appreciation of these various influences.

Because kinetic energy increases with the square of velocity whereas potential energy increases directly with height, large altitude changes at high speed are equivalent to small Mach number changes. As a consequence, if Mach number is to be closely controlled, large altitude changes may be required to maintain flight at a constant energy level. Supersonic cruise aircraft must fly near their limit Mach numbers for maximum efficiency, and therefore very little Mach number change can be tolerated. When Mach number disturbances that can be induced by atmospheric temperature changes are considered, the scope of the problem becomes more apparent. Figure 8 shows the theoretical altitude change required to compensate for a 10° C (18° F) change in atmospheric temperature while maintaining cruise Mach number. The calculation assumes constant energy flight, which implies that Mach number is controlled with the elevons, and the throttles are fixed. The required altitude excursion increases parabolically with cruise Mach number. Consequently, a Concorde aircraft requires almost ten times the altitude change of a B-52 aircraft and a YF-12 aircraft requires twice that of a Concorde aircraft. This situation can be alleviated somewhat by the use of throttle control, but as the pilot comments indicate, throttle response at cruise speeds is sluggish (due to low thrust to weight ratios at cruise). This sluggish response makes it difficult for the pilot to anticipate the results of his control inputs. In addition, excess thrust tends to increase with Mach number for efficient supersonic cruise aircraft, which destabilizes the aircraft's long period modes of motion. When the inlets are fixed, the propulsion system is less efficient and the long period modes are slightly stable or neutral. With the inlets operating automatically, however, the long period motion is divergent. The time history in figure 9 illustrates this effect.

Improved displays, such as the inertial rate of climb and longitudinal acceleration displays, help the pilot cope with these problems. However, an autopilot is still considered necessary to reduce pilot workload for long flights typical of a cruise vehicle. An autopilot using conventional control laws (that is, controlling Mach number with elevons) will induce large altitude excursions, just as a human pilot does. However, studies on the YF-12 simulator have shown that if elevons are used to control altitude and an autothrottle is used to control Mach number, good flight path control can be achieved, even in the presence of atmospheric temperature changes. This is illustrated in figure 10. Concorde experience (ref. 8) has also shown the need for a supersonic cruise autothrottle. Additional information on YF-12 flight research on autopilots for supersonic cruise vehicles can be found in reference 2.

Lateral-Directional Characteristics

Table II summarizes typical YF-12 lateral-directional characteristics throughout the flight envelope. The military specification (ref. 5) requires a minimum Dutch roll frequency of 0.4 radians per second and a minimum Dutch roll damping ratio of 0.15 for level one (satisfactory, normal operation) for takeoff, landing, climb, and cruise for a YF-12-class (class II-L) aircraft. The YF-12 aircraft with SAS on is well within these requirements. The military specification requirement of a maximum roll mode constant, τ_r, of 1.4 seconds is also met. The slightly positive spiral stability is well within the military specification requirement of a time to double of no less than 20 seconds.

Note that the Dutch roll-aileron coupling parameter, $\frac{\omega_\varphi}{\omega_{n_{DR}}}$, is close to 1.0, indicating little or no Dutch roll excitation due to aileron control inputs, throughout the flight envelope. This was achieved without interconnects or special turn coordination channels in the SAS system, which is unusual for an aircraft with a flight envelope as large as that of the YF-12 aircraft. In general, the SAS-on lateral-directional behavior of the aircraft is very good, as the pilot comments indicate.

An interesting aspect of lateral-directional behavior occurs with SAS off above Mach 2.5. Automatic inlet operation causes significant changes in the aircraft's lateral-directional characteristics as compared to the aircraft with inlets fixed. This is illustrated in figure 11, which shows flight data of the aircraft's response to a rudder pulse with the inlets fixed and with the inlets operating automatically. When the inlets are fixed, the Dutch roll oscillations converge, but when the inlets operate automatically, the Dutch roll motions diverge. For a SAS-failed case, the Dutch roll damping meets the military specification requirements with inlets fixed, but with inlets automatic it does not. However, because of the long period of the motion, the aircraft can be safely controlled until SAS is brought back on line or the aircraft decelerates to a lower Mach number. Although complete loss of SAS is a rare occurrence because of the high reliability of the triply redundant system, the YF-12 experience illustrates the need to consider propulsion system effects when evaluating the stability and control characteristics of a supersonic cruise vehicle. It is also interesting to note in table II that automatic inlet operation increases the Dutch roll frequency and changes the phase of w/b. A detailed analysis of these phenomena is contained in reference 9.

CONCLUDING REMARKS

In general, the YF-12 aircraft has very good handling qualities, considering the large flight envelope of the aircraft. Longitudinal and lateral-directional characteristics agree well with existing short period criteria, except for longitudinal damping where both the military specification and the supersonic transport pitch rate response criteria appear to be more stringent than necessary for climb and cruise at higher altitudes.

Pilot comments indicate difficulties with inlet unstarts and long period flight path control. These problems are generic to supersonic cruise vehicles and good criteria for these characteristics do not exist. Improved displays and autopilot functions are needed to provide satisfactory flight path controls. The occurrence of inlet unstarts must be rare and automatic controls may be required to minimize their effects if they do occur.

The influence of the propulsion system on the aircraft's stability and control must be considered when evaluating the aircraft's handling qualities.

Inertial rate of climb and longitudinal acceleration displays in the cockpit help the pilot to establish stabilized conditions.

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TABLE I. —SUMMARY OF PILOT COMMENTS

Takeoff and Landing

Poor ride on rough runway
Very good handling qualities
Good longitudinal control
Good SAS-on damping
Speed stability low
Sensitive throttle

Acceleration and Climb

Speed stability low
Autopilot speed control desired

High-Speed Flight and Cruise

SAS-on longitudinal damping high
SAS-off longitudinal damping low but satisfactory
Speed stability low
High workload to control Mach and altitude
Standard flight path displays inadequate
Inertial displays great improvement
SAS-on lateral-directional damping high
SAS-off lateral-directional damping divergent but controllable
Unstarts disconcerting

TABLE II.—TYPICAL YF-12 LATERAL-DIRECTIONAL CHARACTERISTICS

Flight phase	$\omega_{n_{DR}}$	ζ_{DR}	$\frac{\omega_\varphi}{\omega_{n_{DR}}}$	φ/β		τ_r, sec	τ_s, sec	SAS	Inlet
				Magnitude	Phase, deg				
Takeoff, landing	0.81	0.43	0.96	3.7	52	0.27	190	On	Automatic
[a]Acceleration and climb									
Minimum	1.30	0.36	0.94	1.5	50	0.25	254	On	Automatic
Maximum	2.00	0.61	0.97	2.5	0	0.90	523	On	Automatic
Cruise	1.36	0.43	1.00	0.4	-64	1.20	$>10^6$	On	Automatic
	1.20	-0.01	1.00	0.4	-176	3.50	$>10^6$	Off	Automatic
	1.00	0.06	1.10	0.6	40	4.50	$>10^6$	Off	Fixed

[a]Minimum and maximum values are given because of the wide range of flight conditions in this phase.

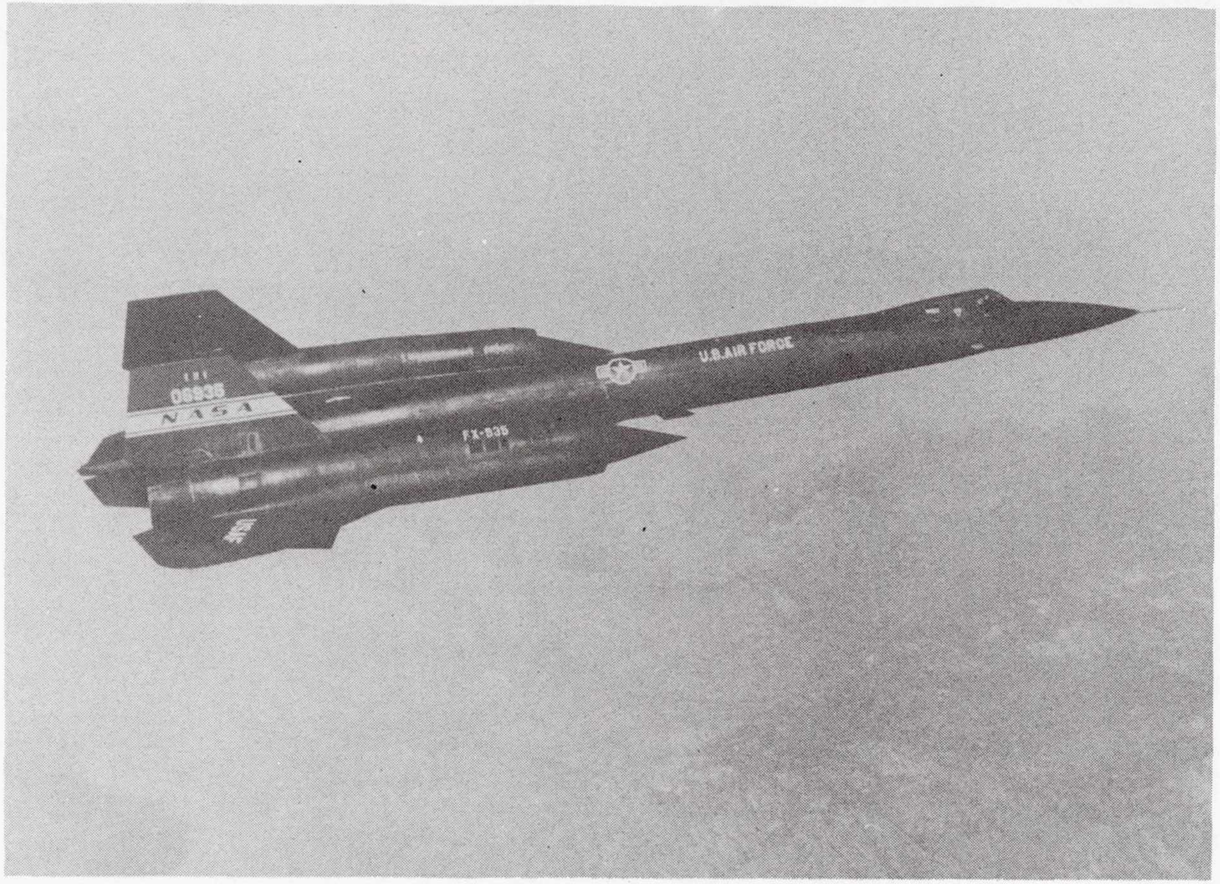


Figure 1.- Test airplane.

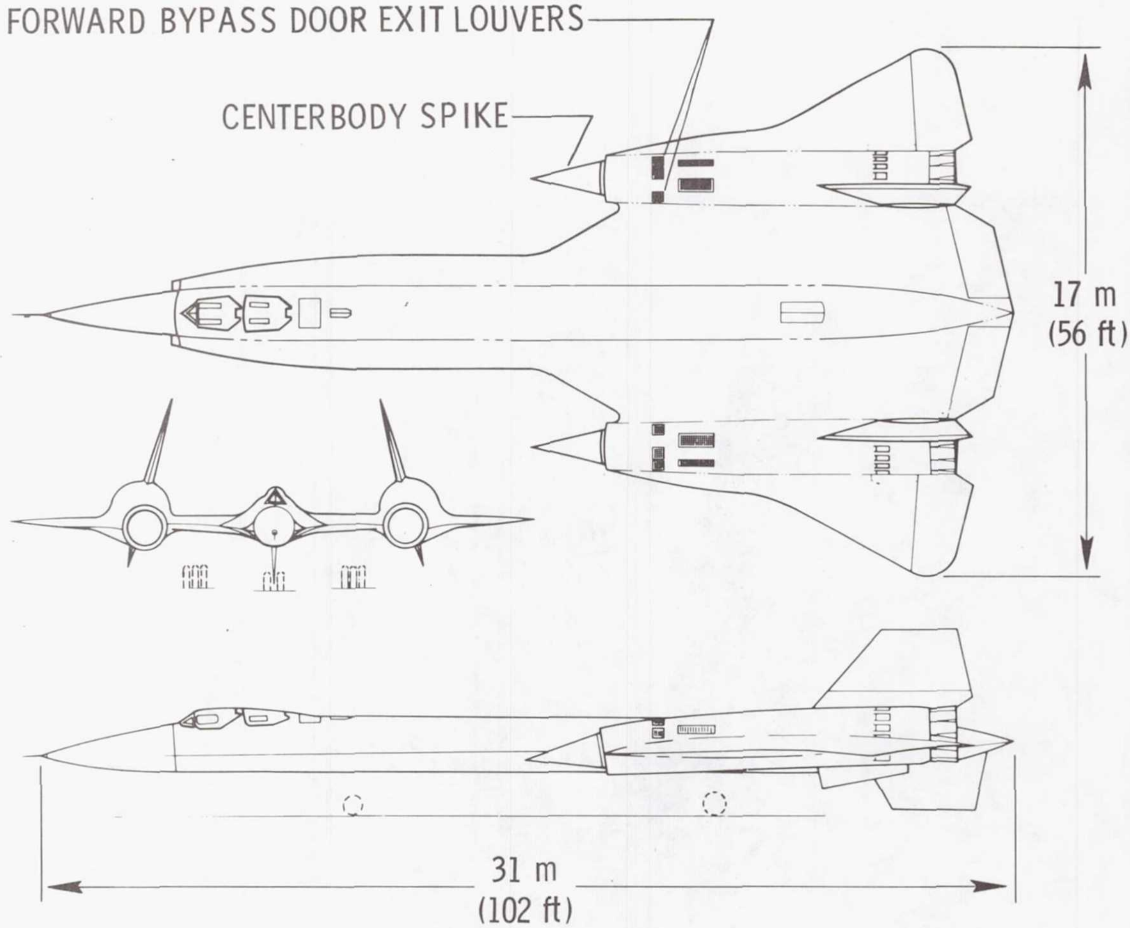


Figure 2.- Three-view drawing of test airplane.

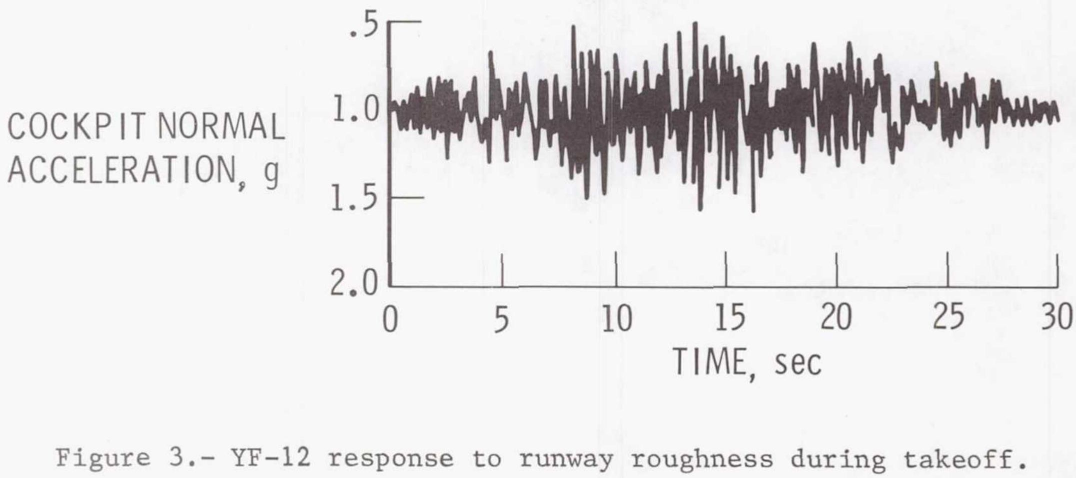
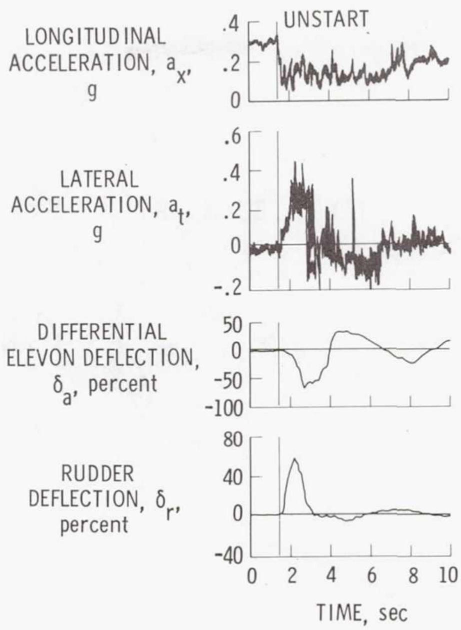
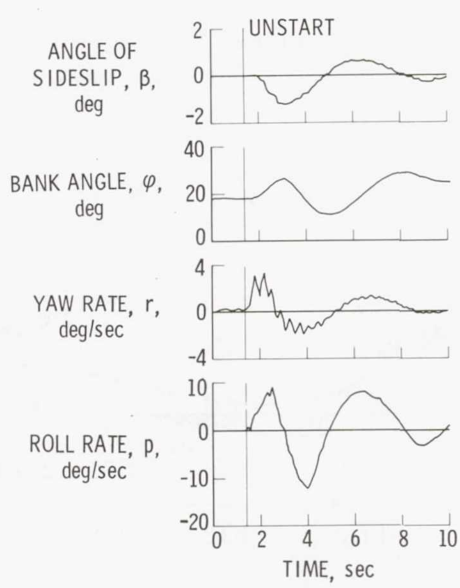


Figure 3.- YF-12 response to runway roughness during takeoff.



(a) a_x, a_t, δ_a, δ_r.



(b) β, φ, r, p.

Figure 4.- Time history of typical unstart. SAS on; inlets automatic. $M \approx 2.7$.

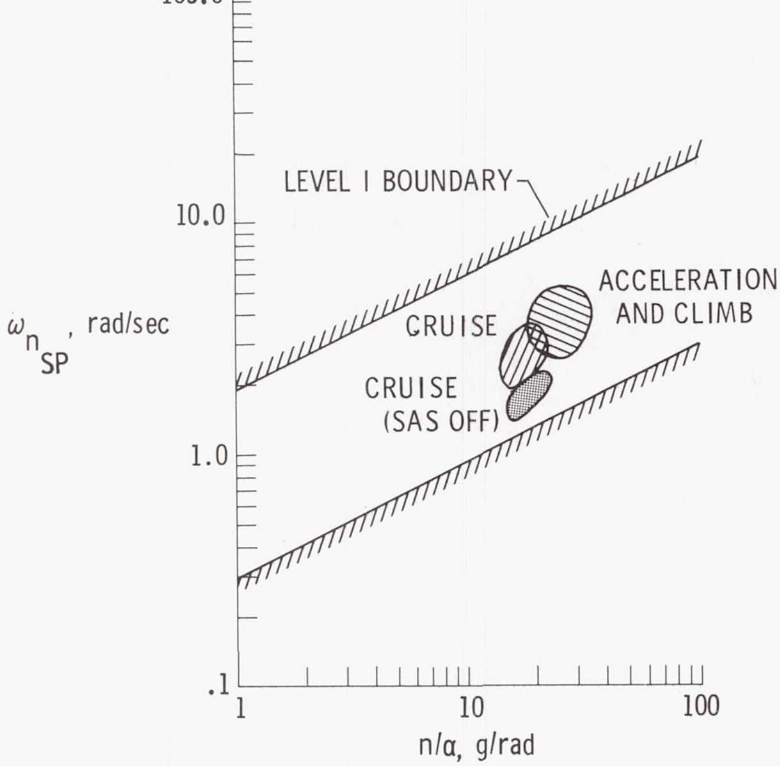


Figure 5.- Typical YF-12 longitudinal characteristics and MIL-F-8785B requirements for acceleration, climb, and cruise.

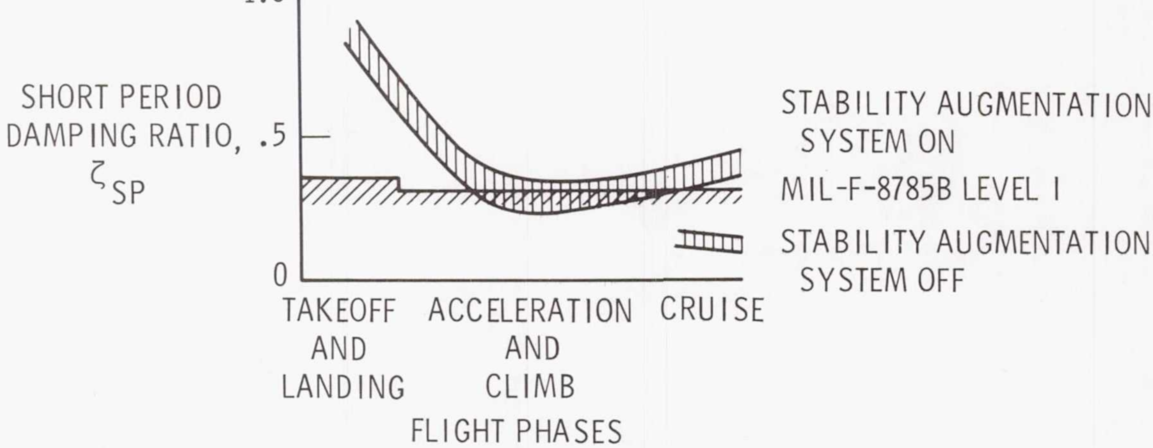
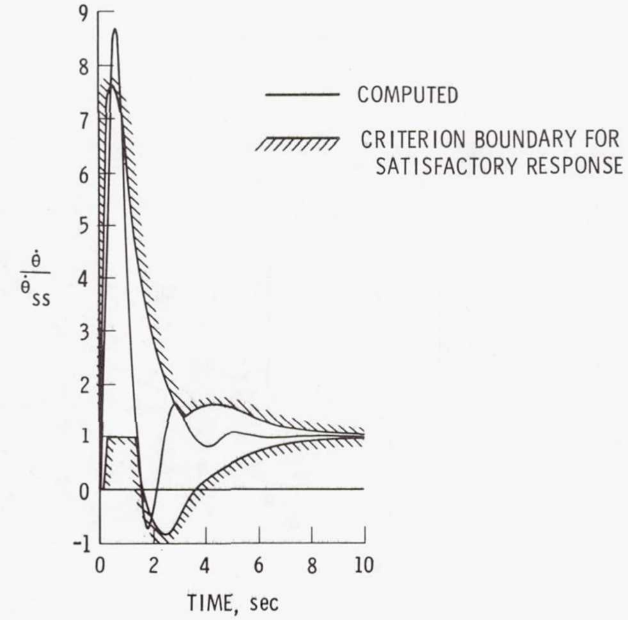
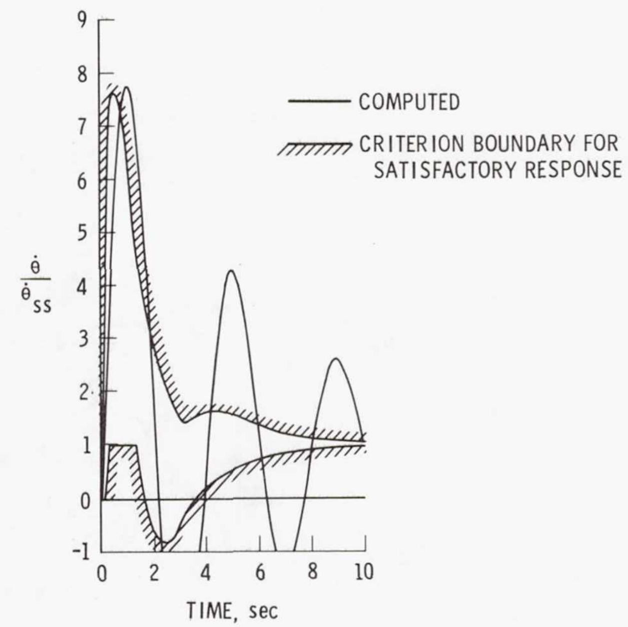


Figure 6.- Typical YF-12 longitudinal short period damping ratios.



(a) Stability augmentation system on.



(b) Stability augmentation system off.

Figure 7.- Comparison of computed YF-12 step responses with modified supersonic transport high-speed pitch rate response criterion.

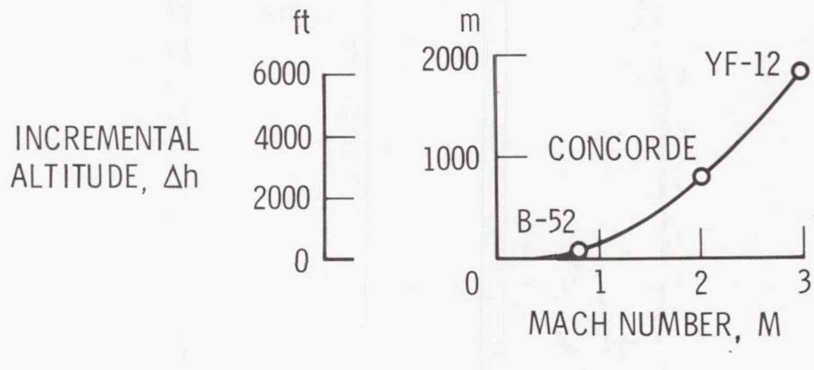


Figure 8.- Altitude change required to compensate for a 10° C (18° F) atmospheric temperature change and maintain Mach number; constant energy flight.

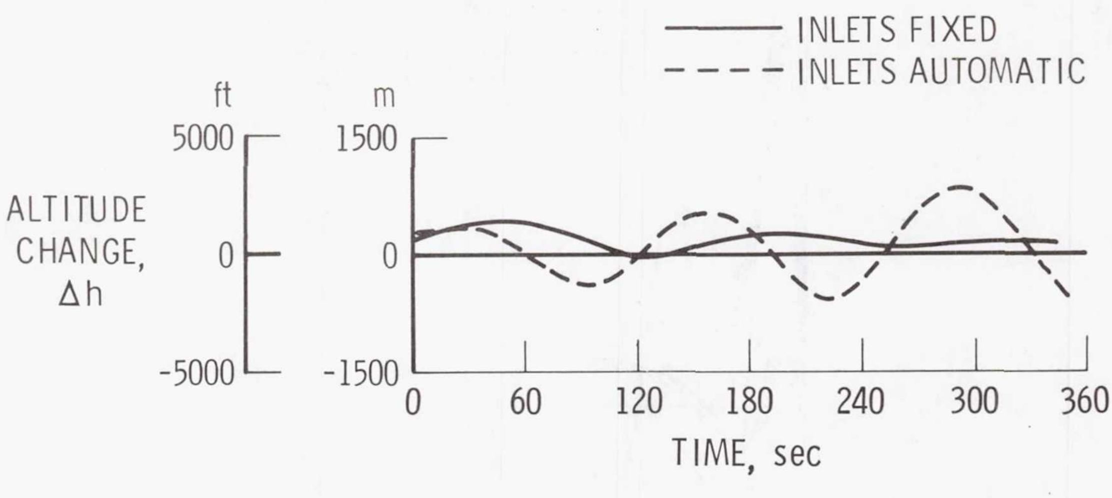


Figure 9.- YF-12 long period response to drag pulse. $M \approx 3.0$.

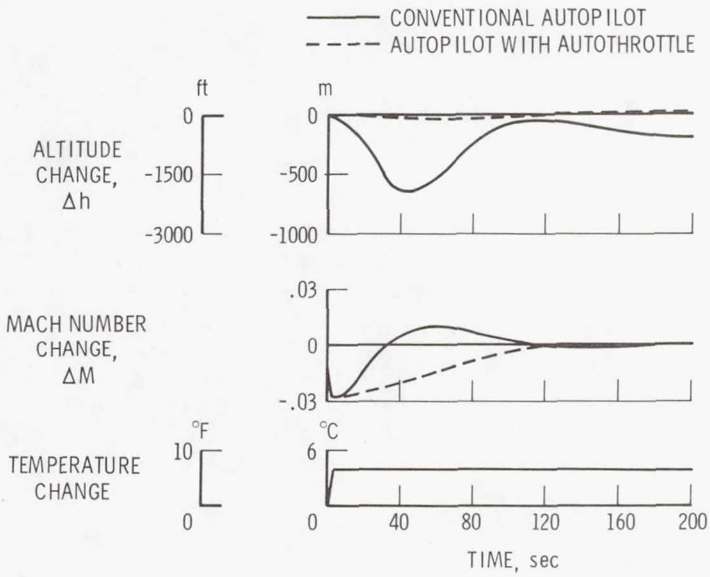


Figure 10.- Mach hold autopilot response. YF-12 simulator; Mach 3.

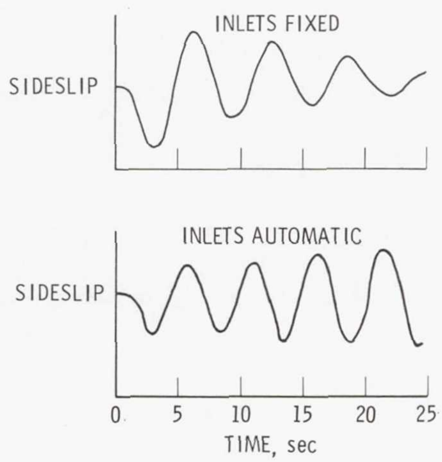


Figure 11.- Dutch roll response. Yaw SAS off; $M \approx 3.0$.