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# TECHNICAL MEMORANDUM

X-514

## CONTROLLABILITY OF THE X-15 RESEARCH AIRPLANE WITH INTERIM ENGINES DURING HIGH-ALTITUDE FLIGHTS

By Euclid C. Holleman and Donald Reisert

Flight Research Center
Edwards, Calif.





NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON

March 1961

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# CONTROLLABILITY OF THE X-15 RESEARCH AIRPLANE WITH INTERIM ENGINES DURING HIGH-ALTITUDE FLIGHTS*

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## SUMMARY

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As part of a general flight test program designed to demonstrate the flight envelope of the X-15 airplane with interim low-thrust engines, flight to high altitude with low dynamic pressure was accomplished. During the program, a peak geometric altitude of 136,500 feet with a minimum dynamic pressure of 10.6 lb/sq ft was attained with only the aerodynamic controls available to the pilot for controlling and stabilizing the airplane. Aerodynamic control was adequate throughout the flight, but at minimum dynamic pressure the airplane was lightly damped, which made precise control difficult. Because of the transient nature of the trajectory and the negligible load factors associated with the airplane oscillation, the pilot did not object to the poor dynamic characteristics of the airplane under these conditions and could satisfactorily control the airplane along the trajectory.

## INTRODUCTION

The X-15 airplane was constructed by North American Aviation, Inc., for the USAF-Navy-NASA program for hypersonic flight research. The airframe was completed before the design rocket engine was available for installation, so initial flight tests (for example, ref. 1) have been conducted with two interim rocket engines of much less thrust than the design engine. References 2 and 3 reported the maximum altitude and Mach number attained by the airplane with the interim engine during the general X-15 flight research program conducted at the NASA Flight Research Center at Edwards, Calif.

Control problems at low dynamic pressure using aerodynamic controls only were anticipated; hence, reaction controls were also designed for the airplane. However, these controls were not available, nor were they

*Title, Unclassified.

required, for the portion of the flight envelope investigated. This paper discusses the high-altitude phase of the program. During this phase, two flights to altitudes greater than 100,000 feet were attained. Particular reference is made to the control characteristics of the airplane at low dynamic pressure with aerodynamic controls.

## SYMBOLS

| | |
|---|---|
| $a_l$ | longitudinal acceleration, g units |
| $a_n$ | normal acceleration, g units |
| $a_t$ | transverse acceleration, g units |
| $C_{1/2}$ | cycles for the airplane oscillation to reduce to half amplitude |
| $F_n$ | center-stick force, lb |
| $g$ | acceleration due to gravity, ft/sec$^2$ |
| $h_p$ | pressure altitude, ft |
| $I_X$ | moment of inertia in roll, slug-ft$^2$ |
| $I_Y$ | moment of inertia in pitch, slug-ft$^2$ |
| $I_Z$ | moment of inertia in yaw, slug-ft$^2$ |
| $I_{XZ}$ | product of inertia, slug-ft$^2$ |
| $L_{\delta_a}\delta_a$ | moment due to full aileron control deflection, ft-lb |
| $M$ | Mach number |
| $M_{\delta_h}\delta_h$ | moment due to full stabilizer control deflection, ft-lb |
| $N_{\delta_v}\delta_v$ | moment due to full rudder control deflection, ft-lb |
| $p$ | rolling velocity, deg/sec |
| $q$ | free-stream dynamic pressure, lb/sq ft |
| $q$ | pitching velocity, deg/sec |
| $r$ | yawing velocity, deg/sec |

| | |
|---|---|
| $t$ | time, sec |
| $\alpha$ | angle of attack, deg |
| $\beta$ | angle of sideslip, deg |
| $\gamma$ | flight-path angle, deg |
| $\delta_a$ | total aileron-control deflection for right and left panels, deg |
| $\delta_h$ | stabilizer-control deflection, deg |
| $\delta_{s_c}$ | longitudinal center-stick position, in. |
| $\delta_v$ | rudder-control deflection, deg |
| $\zeta$ | damping ratio in pitch |
| $\theta$ | pitch angle, deg |
| $\varphi$ | bank angle, deg |
| $\omega_n$ | undamped natural frequency in pitch, radians/sec |

## AIRPLANE

The X-15 airplane (figs. 1 and 2) is a single-place experimental research aircraft designed to explore the hypersonic flight regime at speeds up to 6,600 feet per second and at altitudes up to 250,000 feet. Integral propellant tanks form the major portion of the fuselage, and longitudinal fairings on each side of the airplane house the control cables. An instrument compartment is located behind the cockpit, and the wing is placed well rearward on the fuselage. Variable-deflecting speed brakes are located on the rear fixed portion of the upper and lower vertical tails. The landing gear consists of a corotating dual-wheel nose gear located forward of the cockpit and a main gear equipped with two steel skids located under the tail.

For these tests the X-15 was equipped with two XLR11 rocket motors manufactured by the Reaction Motors Division of the Thiokol Chemical Corp. The motors were mounted one above the other in the rear end of the fuselage. Each rocket motor has four individually controlled cylinders which utilize an alcohol-water mixture as fuel and liquid oxygen as an oxidizer. The combined thrust of the motors is approximately 16,000 pounds at an altitude of 50,000 feet.

A conventional center stick and rudder pedals are provided for control of the airplane. The longitudinal control characteristics of the center stick in terms of stabilizer deflection (fig. 3) indicate a maximum force and deflection gradient of about 1.4 lb/deg and 0.5 in/deg, respectively. The longitudinal control force can be trimmed to zero for a range of horizontal control-surface deflection from 5° leading edge up to 20° leading edge down. In addition to the center stick, a two-axis side-located controller is included for control of pitch and roll in regimes where acceleration forces are expected to compromise effective use of the center stick. This controller, which is mechanically linked to the center-stick system, was not utilized in this investigation. Provision is also made on the X-15 for a ballistic control system consisting of hydrogen-peroxide rockets controlled by a three-axis left-hand controller to give attitude control during flight at low dynamic pressure. This system was not available for the flights reported in this paper.

All aerodynamic control surfaces of the X-15 are actuated by irreversible hydraulic systems. The two-position plain trailing-edge wing flaps are also hydraulically operated. Longitudinal control is provided by deflection of the slab-type horizontal tail; lateral control is provided by differential deflection of the left and right portions of the horizontal tail. When full pitch control is applied, roll control is limited to one surface only. This results in a pitching moment as well as a rolling moment when roll is commanded. The horizontal control-surface rate was limited to 25 degrees per second, and the time lag from stick to surface deflection was approximately 0.04 second. The movable portions of the upper and lower wedge-sectioned vertical tails provide directional control; however, the lower movable section (indicated by the dashed line in fig. 1) is jettisoned prior to landing for ground clearance.

Stability augmentation is provided about all three axes by a rate-sensing damper system which actuates the conventional aerodynamic control surfaces. An interconnect damper system (termed "yar") provides a crossfeed yaw-rate signal into the roll control surfaces. The damper authority is equal to that of the authority of the pilot in pitch and yaw and is twice that of the pilot in roll. Although damper gains may be selected by the pilot, gains of 0.3 deg/deg/sec in pitch, 0.2 deg/deg/sec in roll, 0.24 deg/deg/sec in yaw, and 0.72 deg/deg/sec in yar were used during the two flights considered in this paper.

An inertial data system manufactured by the Sperry Gyroscope Co. is designed to provide the pilot with airplane attitudes about all three axes, as well as inertial velocity and altitude. The airplane angle of attack and angle of sideslip were measured by flow-indicator vanes mounted on a nose boom. These angles were presented to the pilot on conventional dial-type instruments and were superimposed as null readers on a three-axis ball, which also displayed pitch angle, bank angle, and heading.

The X-15 airplane is air-launched from under the right wing of a B-52 carrier aircraft at an altitude of about 45,000 feet and a Mach number of about 0.85. All landings are scheduled to be made on the dry lakebed at Edwards Air Force Base, Calif.

Pertinent physical characteristics of the airplane are presented in table I.

## INSTRUMENTATION

The following quantities pertinent to this investigation were measured by standard NASA instrumentation and were synchronized by a common timer:

Airspeed and pressure altitude
Angle of attack and angle of sideslip
Longitudinal, transverse, and normal accelerations
Pitching, rolling, and yawing angular velocities
Horizontal- and vertical-tail deflections
Control-stick and pedal positions

Airspeed and pressure altitude were measured with an NASA pitot-static tube mounted on a nose boom, and geometric altitude was calculated from ground radar measurements (ref. 2). Airplane pitch and roll attitude were measured by the inertial data system.

## TEST PROGRAM

The tests reported herein are part of the overall flight program for expansion of the X-15 flight envelope into high-altitude regions. An altitude of 80,000 feet was reached during an early flight, but the minimum dynamic pressure obtained was only about 140 psf. One buildup flight was made to familiarize the pilot with the overall piloting task, the steep flight-path angle required, and the airplane handling characteristics at reduced dynamic pressures. The buildup flight also served to check the accuracies of the flight trajectories predicted by the North American Aviation six-degree-of-freedom fixed-base flight simulator for the X-15. The simulator has been an invaluable aid for determining optimum piloting techniques for a desired mission, increasing pilot proficiency for a required control task, and minimizing the number of flights required for exploring the performance capability of the airplane.

For the maximum-altitude flight the pilot's control task required that a constant 8° angle of attack be held during the climb to an altitude of 60,000 feet. At 60,000 feet the airplane was to be accelerated to a Mach number of 1.9, followed by a constant-acceleration pull-up to an angle of attack of either 20° or the maximum angle attainable with full stabilizer deflection. Following fuel burnout, angle of attack was to be reduced to 10° and maintained through re-entry. A pull-out of 3g to level flight completed the maneuver. The pilot was requested to maintain the 10° angle of attack during the low dynamic-pressure portion of the flight by using a minimum of aerodynamic control.

## RESULTS AND DISCUSSION

### Description of Trajectories

The flight plans for the high-altitude buildup flight (fig. 4) and the maximum-altitude flight (fig. 5) were generally similar. The X-15 was launched, with all dampers operating, approximately 100 miles from the intended landing site on a near straight-in heading at an altitude of approximately 45,000 feet and a Mach number of about 0.85. After launch, a normal engine start was accomplished and, with all eight cylinders burning, a climb at maximum lift-drag ratio was initiated by flying at a nearly constant 8° angle of attack. Angle of attack was reduced to bring the aircraft to level flight at approximately 60,000 feet. The airplane was then accelerated to $M = 1.9$ where, for the buildup flight (fig. 4), power was reduced to six cylinders of the rocket engine and a 1.5g pull-up to an angle of attack of 15° was initiated. An angle of attack of 15° and a maximum pitch angle of about 28° were attained almost simultaneously with the occurrence of burnout ($t = 290$ sec). An altitude of approximately 107,000 feet was reached subsequently, with the dynamic pressure diminishing to approximately 62 lb/sq ft. Although angle of attack varied somewhat during re-entry, a peak normal acceleration of only about 2.6g was required during the pull-out, with the dynamic pressure reaching a maximum of 460 lb/sq ft. Level flight was achieved at an altitude of about 50,000 feet.

For the maximum-altitude flight (fig. 5) full power was maintained until fuel burnout. While accelerating, at a Mach number of 1.75 and an altitude of 60,000 feet, the gain in pitch of the stability-augmentation system was reduced to zero and a pulse was performed in the longitudinal mode. After about 4 cycles of airplane oscillation, the damper was reengaged, and, at a Mach number of 1.9, a pull-up was initiated until the angle of attack reached approximately 18.5°. Full back-stick deflection was necessary to maintain this angle of attack during the climb; this condition simplified the longitudinal piloting task although the stick force was high, but complicated the roll control task because of the limitation of available differential control. During this period the flight-path angle rotated to a maximum of 30° and the pitch attitude to about 48°. At $t = 265$ seconds, burnout occurred (due to propellant exhaustion) at an altitude of 116,500 feet and a Mach number of 1.93. The pilot then decreased the angle of attack to approximately 10°; however, the deflection of the stabilizer initiated a ±4° pitching oscillation with a period of about 8 seconds. After 4 cycles, the oscillation was reduced to an amplitude of ±1° by the pilot and the pitch damper. During the last portion of this oscillation, the airplane achieved the peak of the trajectory. A maximum pressure altitude of 133,900 feet was obtained at a static pressure of 5.6 lb/sq ft based on the U.S. Extension to the ICAO Atmosphere. The corresponding peak geometric altitude was 136,500 feet. The Mach number at the peak altitude was 1.63 at a minimum dynamic pressure of 10.6 lb/sq ft. The normal acceleration remained below 0.1g for 57 seconds. An angle of attack of approximately 11° was maintained as the flight-path angle decreased for re-entry. Maximum dynamic pressure was 785 lb/sq ft during the recovery. Two rudder pulses were performed by the pilot at $t = 395$ seconds and $t = 405$ seconds to document the dynamic directional characteristics of the airplane (roll and yaw dampers off). Level flight was accomplished at an altitude of about 46,000 feet.



## Comparison With Predicted Trajectory

The time variations of altitude and dynamic pressure for the maximum-altitude flight are compared in figure 6 with that predicted on the X-15 fixed-base flight simulator prior to the flight. Although the desired flight plan was not followed exactly during the climb and descent, the maximum altitude and associated dynamic pressure attained in flight agreed well with simulated values. In actual flight, burnout occurred at a lower altitude but at a higher speed than on the simulated flight; therefore, the total energy was approximately the same, which resulted in similar peak altitudes.

## Airplane Characteristics at Low Dynamic Pressure

The airplane dampers were operating during the maximum-altitude flight, yet the overall damping of the airplane in the low-dynamic-pressure region was light. Precise control of the airplane was difficult at a dynamic pressure of 70 lb/sq ft ($t = 240$ sec, fig. 6), where a pilot-induced oscillation is indicated.

No asymmetrical burnout moments were reported, but an airplane oscillation was triggered as the push-over to an angle of attack of 10° was made. However, the pilot was able to stabilize the airplane to within 2° of the desired value even though the airplane damping was light.

To determine the effectiveness of the pitch damper at this low dynamic pressure, the number of cycles to damp to half amplitude was calculated as a function of dynamic pressure for the basic airplane and for two pitch-damper gains. These gains were (1) the values used during flight and (2) the maximum available to the pilot. The calculations indicated (fig. 7) that the airplane characteristic motions were four to five times more heavily damped with the damper operating at flight gain. Maximum damper gain would have resulted in increasing the damping by an additional factor of 2. The actual damping ratio $\zeta$ of the airplane at the flight condition tested was about 0.05. Pilots have described airplane response with dynamic characteristics similar to the X-15 at this flight condition as initially sluggish, followed by a persistent, lightly damped oscillation which is susceptible to overcontrol.

The pilot was requested to "fly" the practice flights on the simulator exactly as specified in the actual flight plan; however, he usually did not attempt to damp the airplane oscillations during the low dynamic pressure portion of the flight, perhaps because of lack of environmental visual cues or motivation. In flight, however, the pilot damped the oscillation to small amplitude within four cycles, although there were no perceptible aerodynamic loads associated with the airplane oscillation. The most effective piloting technique required deliberate, precisely timed control inputs. The longitudinal period at this flight condition was about 8 seconds, which was well within the capability of the pilot to function as a damper.

The X-15 basic aerodynamic control power proved to be satisfactory throughout the maximum-altitude flight. At a dynamic pressure of 30 lb/sq ft, the pilot slowly reduced the vehicle angle of attack from about 18° to about 10° by using the aerodynamic controls. At a dynamic pressure of 10.6 lb/sq ft, the aerodynamic controls were effective for stabilizing the airplane near the desired angle of attack and for damping the oscillation induced by a change in attitude. The aerodynamic control available to the pilot as estimated from wind-tunnel data for a Mach number of 2 and an angle of attack of 10° is indicated in figure 8 as a function of dynamic pressure. For comparison, the design reaction-control effectiveness is also included. At a dynamic pressure of 10 lb/sq ft, the aerodynamic controls in pitch (up) and roll are as effective as the design reaction controls. The rudder control is not as effective as the reaction control; however, the data of figure 5 indicate that the pilot used little yaw control during this flight. In pitch, only about 15 percent of the available aerodynamic control was used; in roll, only about 25 percent was used.

## Pilot Comments

Following the flight, the X-15 pilot was requested to comment on the controllability of the airplane and the adequacy of the pilot's presentation. In general, the pilot felt that the airplane response was good, but that attention was required for precise control. The cockpit instrument presentation was considered satisfactory for all control tasks.

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As was indicated on the flight simulator, the most difficult control tasks occurred during the climb at high angle of attack with near-maximum stabilizer deflection and during the push-over as maximum altitude was approached. During the push-over, in which the airplane motions were very lightly damped, the pilot indicated that the controllability of the airplane was acceptable but that precise control was too demanding because of light damping. Control motion was deliberately "nice and easy" to avoid disturbing the airplane in this region of low dynamic pressure.

A wide range of airplane dynamics was evaluated (ref. 4) in flight with a variable-stability airplane to determine regions of dynamics considered by the pilot to be "best," "acceptable," and "unsatisfactory." Based on the study of reference 4 (fig. 9), the longitudinal characteristics of the X-15 airplane at low dynamic pressure would be predicted to be "unsatisfactory." However, the pilot rated the airplane as "marginally acceptable," which indicates that more than desired pilot attention generally was necessary. At higher dynamic pressures (100 to 200 psf), the ratings were, generally, in accord with the criteria of reference 4. The referenced boundaries, it should be noted, were the result of relatively long duration evaluations, whereas the X-15 pilot was exposed to the poor dynamics for only a short time. Thus, the X-15 results do indicate that the pilot can control poor airplane dynamics for short periods.

For the maximum-altitude flight, as well as other X-15 flights, the pilot "flew" the flight plan on the fixed-base flight simulator prior to the actual flight. He indicated that the cockpit-display cues provided by the simulator for control technique and performance matched closely those encountered in flight. Therefore, the pilot felt the simulator was an excellent means of preparing for this flight.

## CONCLUDING REMARKS

An investigation of the controllability of the X-15 airplane with aerodynamic controls at low dynamic pressure indicated that trajectories to a dynamic pressure of 10.6 lb/sq ft could be controlled adequately. At low dynamic pressure, the damping of the airplane characteristic motions was light, even with a moderate-gain pitch damper. This condition resulted in easily excited and sustained oscillations of low frequency. The pilot could, without reaction controls, accomplish the desired trajectory control task, inasmuch as transient conditions occurred through most of the flight and the poor control conditions encountered were of relatively short duration.

Flight Research Center, H
National Aeronautics and Space Administration, 2
Edwards, Calif., January 4, 1961. 1
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2. Stillwell, Wendell H., and Larson, Terry J.: Measurement of the Maximum Altitude Attained by the X-15 Airplane Powered With Interim Rocket Engines. NASA TN D-623, 1960.

3. Stillwell, Wendell H., and Larson, Terry J.: Measurement of the Maximum Speed Attained by the X-15 Airplane Powered With Interim Rocket Engines. NASA TN D-615, 1960.

4. Chalk, Charles R.: Additional Flight Evaluations of Various Longitudinal Handling Qualities in a Variable-Stability Jet Fighter. Part II. WADC Tech. Rep. 57-719 (Contract No. AF 33(616)-3990). Wright Air Dev. Center, U.S. Air Force, July 1958.

TABLE I.- PHYSICAL CHARACTERISTICS OF THE AIRPLANE

| | |
|---|---|
| **Wing:** | |
| Airfoil section | NACA 66005 (Modified) |
| Total area (includes 94.98 sq ft covered by fuselage), sq ft | 200 |
| Span, ft | 22.36 |
| Mean aerodynamic chord, ft | 10.27 |
| Root chord, ft | 14.91 |
| Tip chord, ft | 2.98 |
| Taper ratio | 0.20 |
| Aspect ratio | 2.50 |
| Sweep at 25-percent-chord line, deg | 25.64 |
| Incidence, deg | 0 |
| Dihedral, deg | 0 |
| Aerodynamic twist, deg | 0 |
| Flap - | |
| Type | Plain |
| Area (each), sq ft | 8.30 |
| Span (each), ft | 4.50 |
| Inboard chord, ft | 2.61 |
| Outboard chord, ft | 1.08 |
| Deflection, down (nominal design), deg | 40 |
| Ratio flap chord to wing chord | 0.22 |
| Ratio total flap area to wing area | 0.08 |
| Ratio flap span to wing semispan | 0.40 |
| Trailing-edge angle, deg | 5.67 |
| Sweepback angle of hinge line, deg | 0 |
| **Horizontal tail:** | |
| Airfoil section | NACA 66005 (Modified) |
| Total area (includes 63.29 sq ft covered by fuselage), sq ft | 115.34 |
| Span, ft | 18.08 |
| Mean aerodynamic chord, ft | 7.05 |
| Root chord, ft | 10.22 |
| Tip chord, ft | 2.11 |
| Taper ratio | 0.21 |
| Aspect ratio | 2.83 |
| Sweep at 25-percent-chord line, deg | 45 |
| Dihedral, deg | -15 |
| Ratio horizontal-tail area to wing area | 0.58 |
| Movable surface area, sq ft | 51.77 |
| Deflection - | |
| Longitudinal, up, deg | 15 |
| Longitudinal, down, deg | 35 |
| Lateral differential (pilot authority), deg | ±15 |
| Lateral differential (autopilot authority), deg | ±30 |
| Control system | Irreversible hydraulic boost with artificial feel |
| **Upper vertical tail:** | |
| Airfoil section | 10° single wedge |
| Total area, sq ft | 40.91 |
| Span, ft | 4.58 |
| Mean aerodynamic chord, ft | 8.95 |

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TABLE I.- PHYSICAL CHARACTERISTICS OF THE AIRPLANE - Concluded

| | |
|---|---|
| Root chord, ft | 10.21 |
| Tip chord, ft | 7.56 |
| Taper ratio | 0.74 |
| Aspect ratio | 0.51 |
| Sweep at 25-percent-chord line, deg | 23.41 |
| Ratio vertical-tail area to wing area | 0.20 |
| Movable surface area, sq ft | 26.45 |
| Deflection, deg | ±7.50 |
| Sweepback of hinge line, deg | 0 |
| Control system | Irreversible hydraulic boost with artificial feel |
| **Lower vertical tail:** | |
| Airfoil section | 10° single wedge |
| Total area, sq ft | 34.41 |
| Span, ft | 3.83 |
| Mean aerodynamic chord, ft | 9.17 |
| Root chord, ft | 10.21 |
| Tip chord, ft | 8 |
| Taper ratio | 0.78 |
| Aspect ratio | 0.43 |
| Sweep at 25-percent-chord line, deg | 23.41 |
| Ratio vertical-tail area to wing area | 0.17 |
| Movable surface area, sq ft | 19.95 |
| Deflection, deg | ±7.50 |
| Sweepback of hinge line, deg | 0 |
| Control system | Irreversible hydraulic boost with artificial feel |
| **Fuselage:** | |
| Length, ft | 50.75 |
| Maximum width, ft | 7.33 |
| Maximum depth, ft | 4.67 |
| Maximum depth over canopy, ft | 4.97 |
| Side area (total), sq ft | 215.66 |
| Fineness ratio | 10.91 |
| **Speed brake:** | |
| Area (each), sq ft | 5.57 |
| Span (each), ft | 1.67 |
| Chord (each), ft | 3.33 |
| Deflection, deg | 35 |

| | Launch | Landing |
|---|---|---|
| Weight, lb | 33,517 | 14,318 |
| Center-of-gravity location, percent mean aerodynamic chord | 20.5 | 18.5 |
| **Moments of inertia:** | | |
| $I_X$, slug-ft$^2$ | 5,200 | 3,600 |
| $I_Y$, slug-ft$^2$ | 108,200 | 85,000 |
| $I_Z$, slug-ft$^2$ | 110,500 | 86,500 |
| $I_{XZ}$, slug-ft$^2$ | -1,000 | -650 |

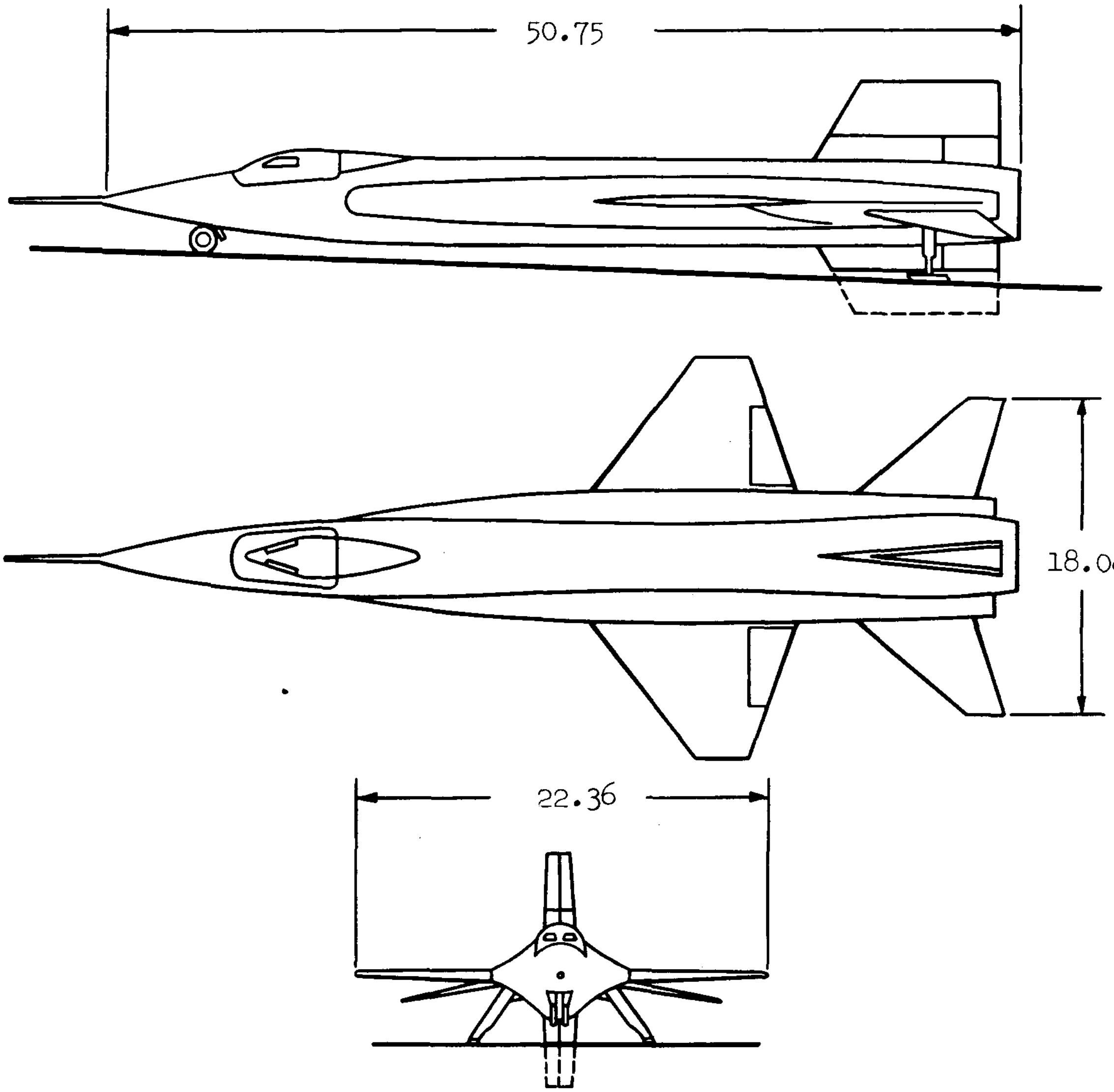


Figure 1.- Three-view drawing of the X-15 airplane. All dimensions in feet.

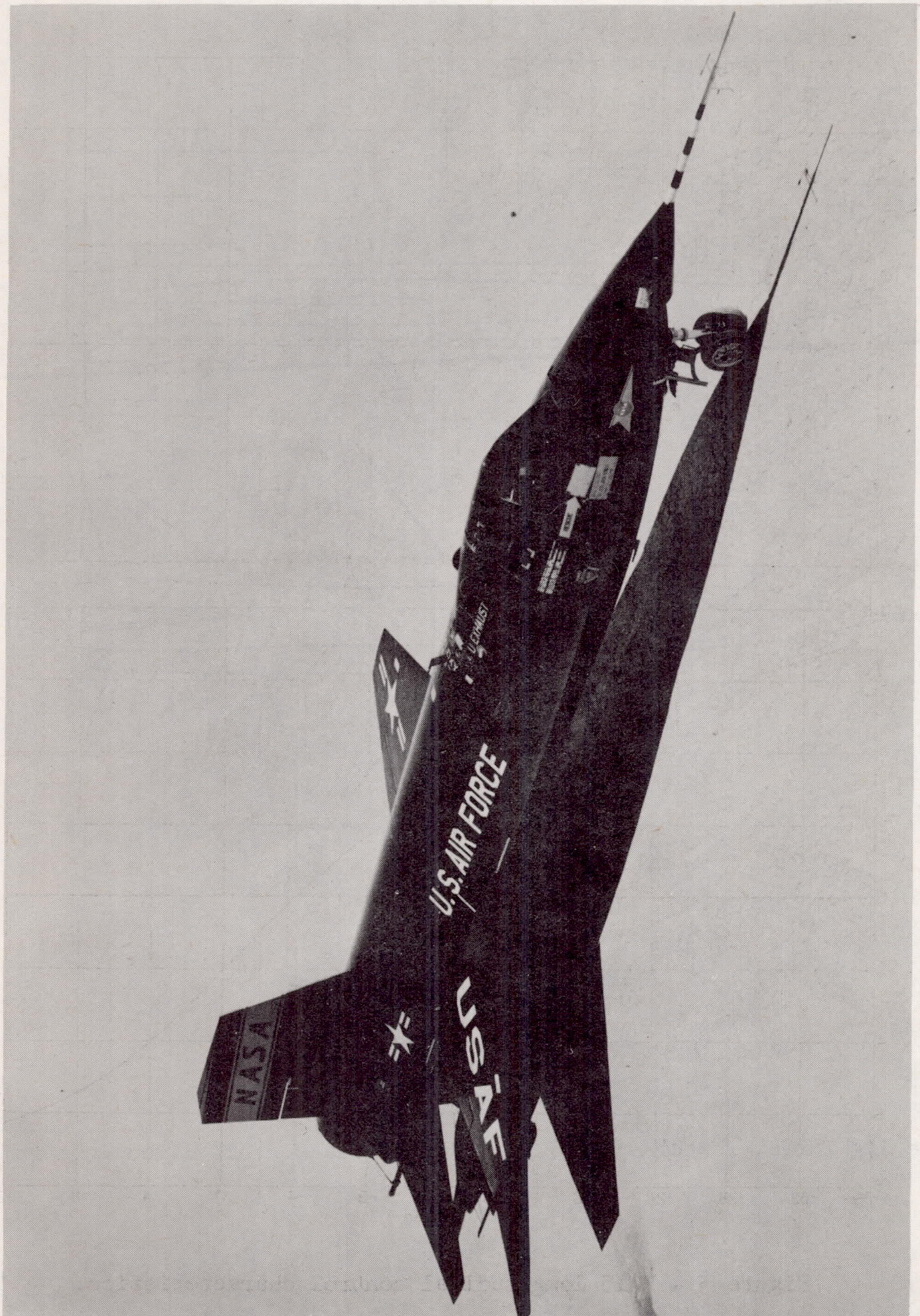


Figure 2.- Photograph of the X-15 airplane.

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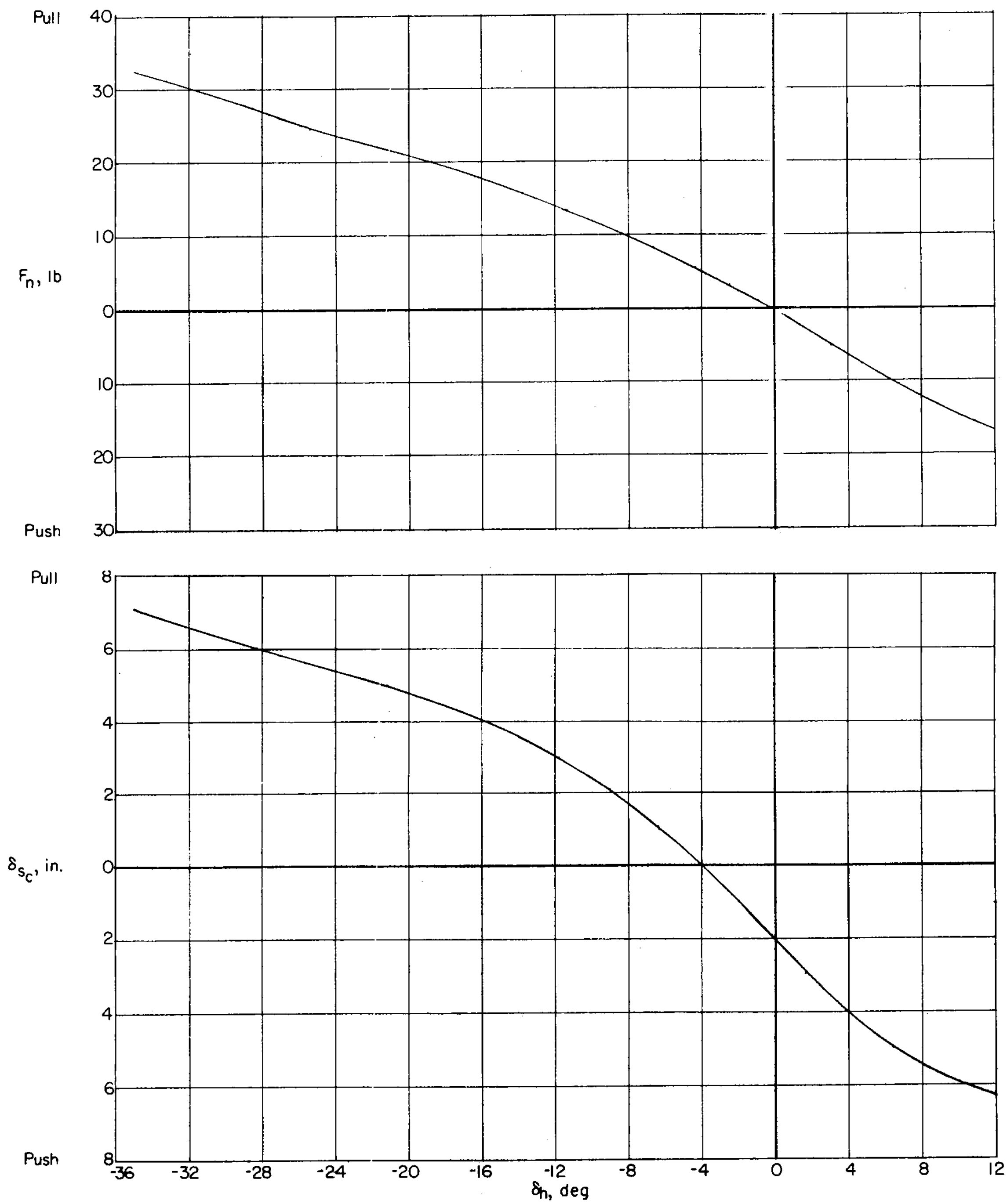


Figure 3.- X-15 longitudinal control characteristics.

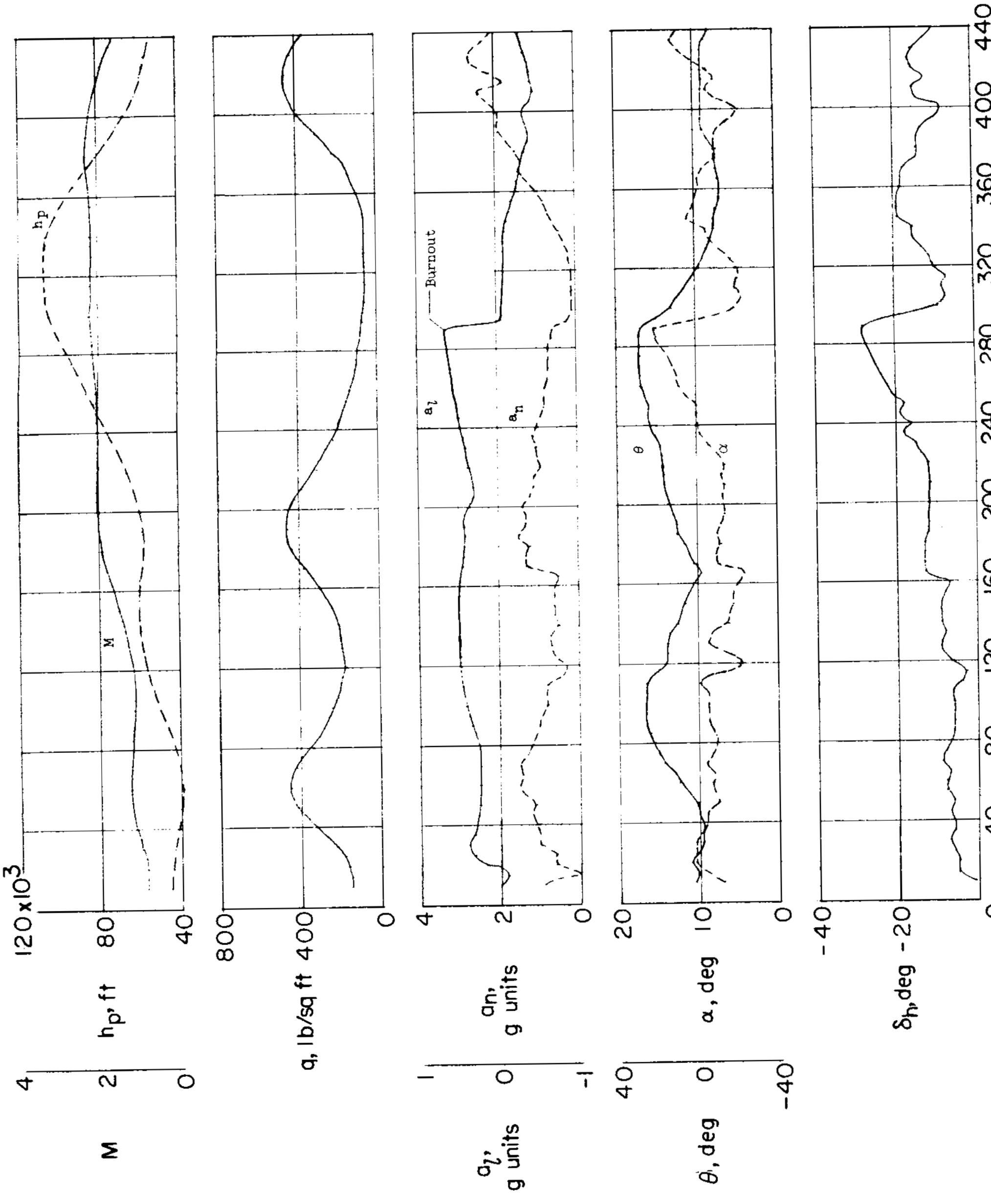


Figure 4.- Time history of X-15 maximum-altitude buildup flight.

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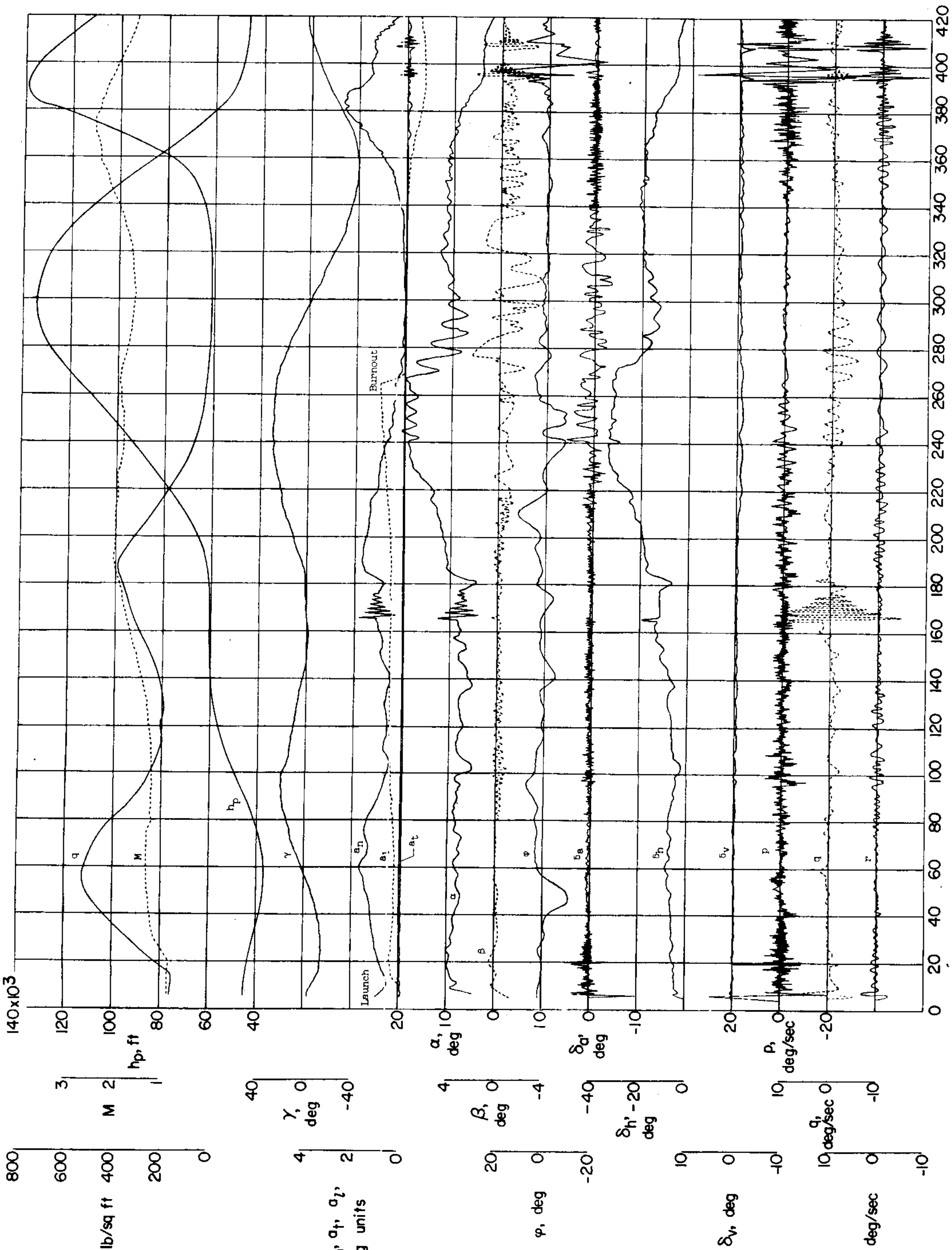


Figure 5.- Time history of the X-15 maximum-altitude flight.

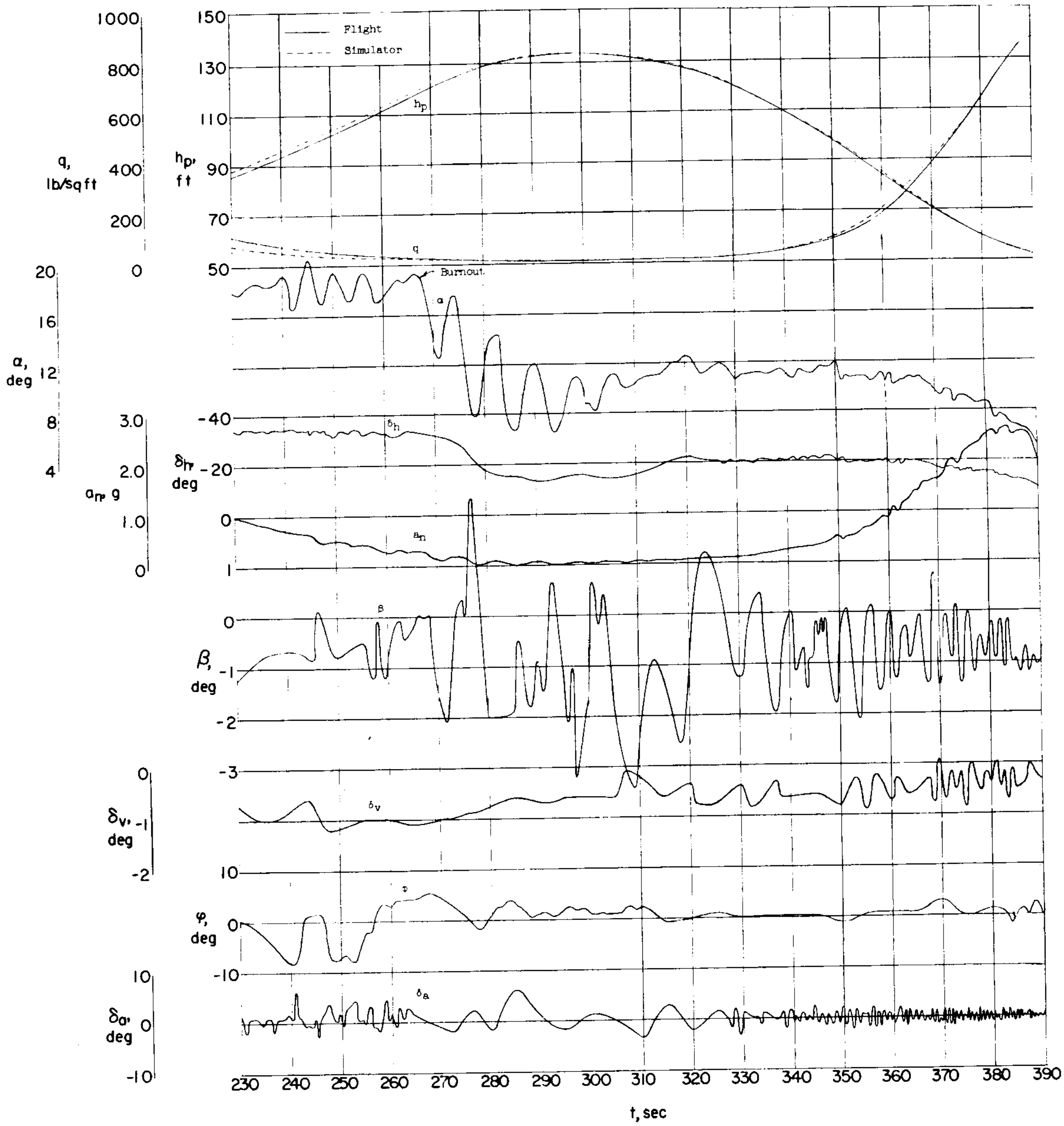


Figure 6.- Low dynamic portion of the X-15 maximum-altitude flight.

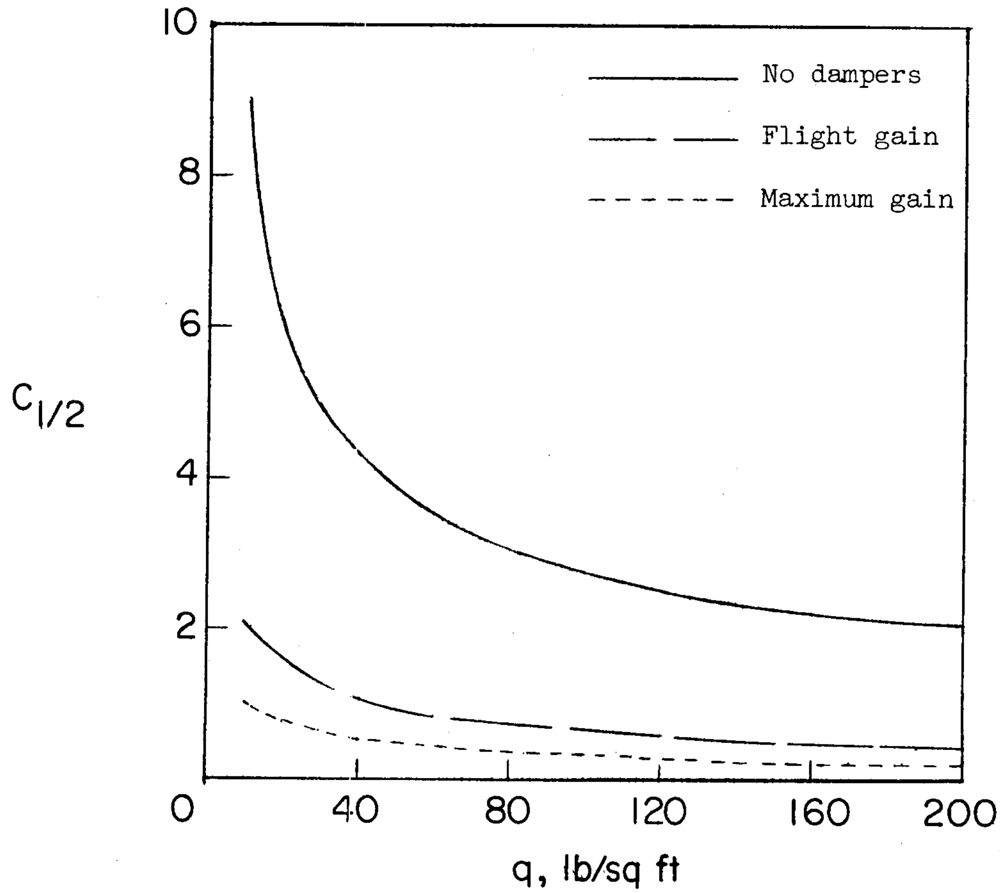


Figure 7.- Calculated damping characteristics of the X-15 in pitch.

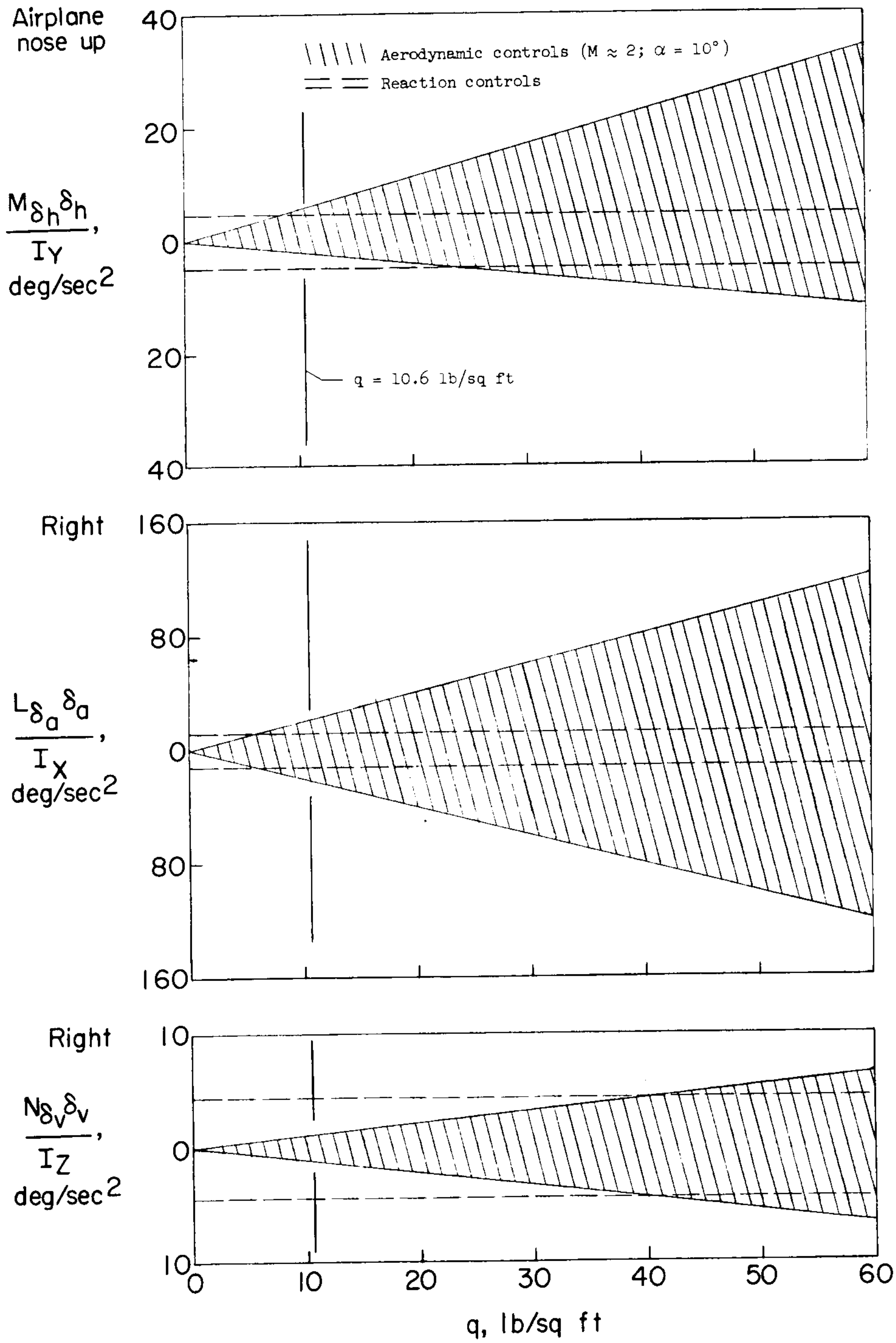


Figure 8.- Comparison of X-15 aerodynamic-control effectiveness with reaction-control effectiveness.

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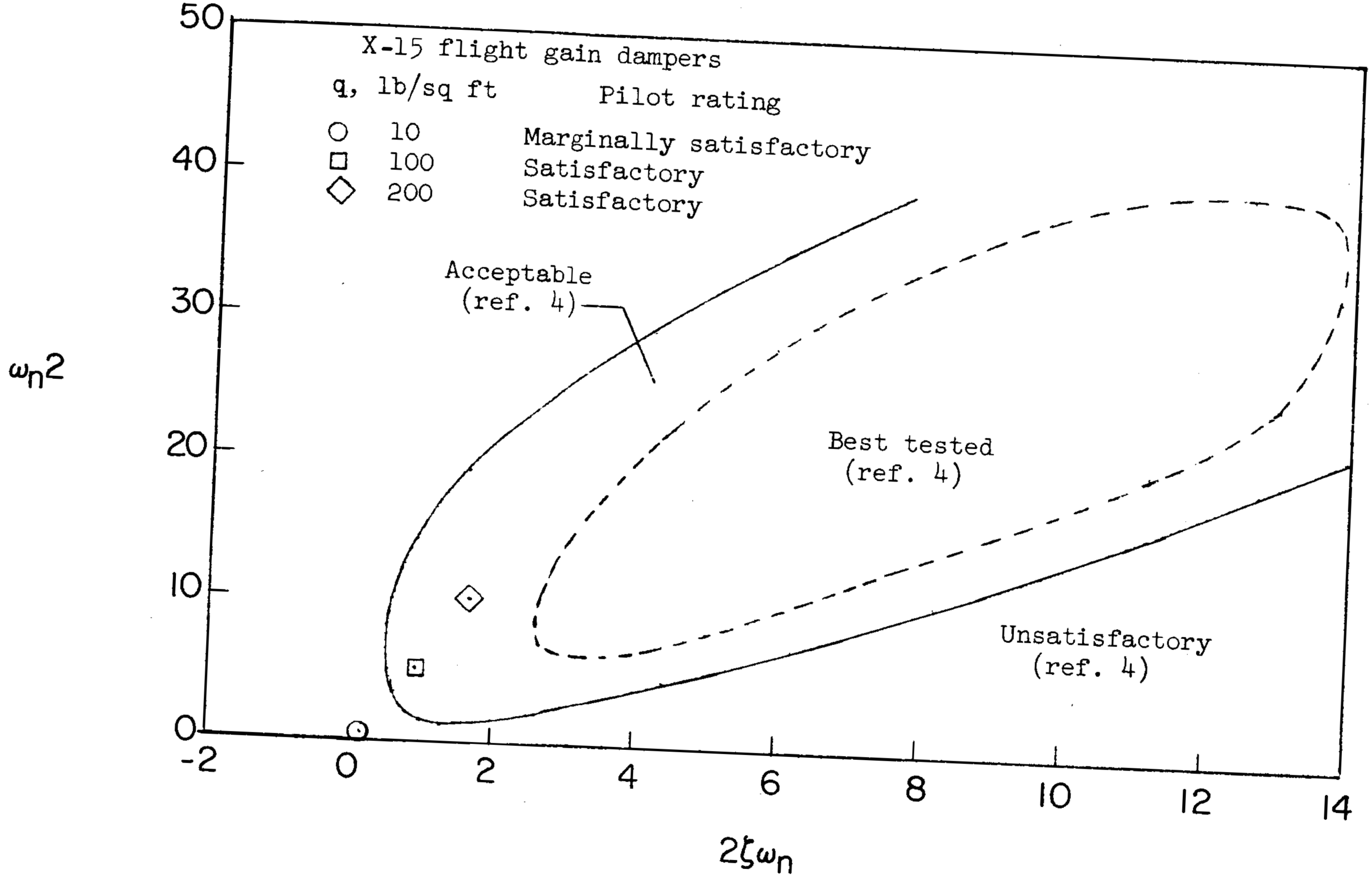


Figure 9.- Comparison of the X-15 longitudinal characteristics at high altitude with the pilot-determined boundaries of reference 4.

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