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NASA TN D-3262

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • FEBRUARY 1966

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CONTROL EXPERIENCES OF THE X-15 PERTINENT TO LIFTING ENTRY*

By Euclid C. Holleman
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SUMMARY

In the program to expand the flight envelope of the X-15 airplane, flights to and entries from altitudes up to 350,000 feet have been accomplished. During these entries, flight-control experience was obtained with four different control-system configurations having varying degrees of complexity. The high steady acceleration and rapidly changing aerodynamic environment did not affect the pilot's capability to control the entry. All the control systems evaluated were judged by the pilots to be satisfactory for the control of the X-15 entry from the design altitude. Entries have been made that presented more severe control problems than predicted for entries of advanced vehicles at higher velocities.

INTRODUCTION

At the time of the last Conference on the Progress of the X-15 Project, in 1961, the immediate goal of the X-15 program was the expansion of the flight envelope of the airplane. An altitude of 217,000 feet had been reached in preparation for flights to the design altitude of 250,000 feet. During this early part of the project, several problems were encountered that threatened to curtail the program. Some of these problems were the general controllability (ref. 1) of the basic airplane and the reliability of the inertial and stability augmentation systems (ref. 2). However, these difficulties were solved and the original program objectives have been accomplished.

The purpose of this paper is to discuss the flight experiences in recovering the X-15 airplanes from high altitude with conventional and adaptive controls, and to place these experiences in proper perspective relative to future lifting-entry programs.

*This paper was included in a classified report entitled "Fourth Conference on Progress of the X-15 Research Airplane Program," Flight Research Center, Oct. 7, 1965. NASA SP-90, 1965.

SYMBOLS

a_x	longitudinal acceleration, g units
a_y	lateral acceleration, g units
a_z	normal acceleration, g units
g	acceleration due to gravity, feet per second^2
h	altitude, feet
L_{δ_a}	roll acceleration due to aileron deflection, 1/second^2
M	Mach number
M_{δ_h}	pitch acceleration due to horizontal-tail deflection, 1/second^2
N_{δ_r}	yaw acceleration due to vertical-tail deflection, 1/second^2
p	rolling velocity, degrees per second
q	dynamic pressure, pounds per square foot
t	time, seconds
V	velocity, feet per second
α	angle of attack, degrees
β	angle of sideslip, degrees
φ	angle of bank, degrees
δ_a	aileron deflection, radians
δ_h	horizontal-tail deflection, radians
δ_r	vertical-tail deflection, radians

Subscripts:

AV	average
MAX	maximum

HIGH-ALTITUDE AND ENTRY EXPERIENCE

A time history of a flight to an altitude of 354,200 feet (fig. 1) illustrates the type of mission the X-15 is capable of. Following launch at about 45,000 feet, the pilot advances the throttle and climbs to high altitudes into the region of extremely low dynamic pressure. After maximum altitude is reached, during descent, the pilot stabilizes the airplane at the desired angle of attack for reentry. Reentry flight-path angle is high, approximately 38° for this flight. The buildup in dynamic pressure, acceleration, and temperature is rapid but of short duration.

Entries have been made with each of two variations of two basic control systems. Two X-15 airplanes are equipped with conventional aerodynamic controls with stability augmentation and acceleration command reaction controls. Backup aerodynamic damping augmentation has been added for redundancy, and reaction augmentation has been added for increased controllability at low dynamic pressure. Another X-15 airplane is equipped with an adaptive control system, the MH-96 flight control system, which was developed under Air Force contract for evaluation in advanced vehicles. The X-15 program provided the opportunity to evaluate the design capabilities of the system in actual entry flight. The system has adaptive gain-changing rate-command aerodynamic and rate-command reaction controls in all three control axes, blended aerodynamic and reaction controls, attitude command or hold modes, and normal-acceleration limiting.

Flight experience with the X-15 during high-altitude flights and entries with these controls is summarized in table I. Since 1961, the design altitude has been demonstrated by using the airplanes with conventional and adaptive control systems, and flights to much higher altitudes have been made with the airplanes equipped with the adaptive control system. Since 1962, all flights have been made with the lower ventral removed, because it was found that the airplane configuration without the lower ventral was more controllable (ref. 3).

The X-15 entry control task requires the pilot to establish and hold the desired angle of attack until normal acceleration builds to the desired value, and then to hold normal acceleration until a constant glide angle of attack or constant rate of descent is achieved.

By means of this control technique, entries from high altitudes have been made to cover a wide range of entry parameters: average values of entry angle of attack α_{AV}, maximum values of normal acceleration $(a_Z)_{MAX}$, and maximum dynamic pressure q_{MAX} (fig. 2). These values are not unique functions of the maximum altitude, since they may be altered by piloting technique; however, they represent the entry experience obtained. The design altitude of 250,000 feet is shown for reference. Entry angle of attack has varied from about 12° to 20° during entries from the lower altitudes. During entries from higher altitudes, angles of attack up to about 25° were used. The use of entry angles of attack higher than these values is not planned, inasmuch as trim capability is limited because of the increased static longitudinal stability at high angle of attack. Also, some control must be reserved for the stability augmentation system.

A range of normal acceleration of only about 3g to 5g has been covered, since higher accelerations were not required for recovery and there was no need to test to the design limit of the airplane. A wide range of entry dynamic pressure was covered, inasmuch as this quantity is more critically dependent on piloting technique. Maximum entry dynamic pressure was about 1900 pounds per square foot.

ENTRY CONTROL EXPERIENCE

During flights to high altitudes, the control problems of lifting entry at relatively low velocities have been met and solved by utilizing the attributes of the pilot and the automatic systems. Entries have been accomplished in a variety of entry environments and with several degrees of control-system sophistication.

A comparison of entry controllability with the most and the least sophisticated control systems is shown in figure 3. The entries were made with the ventral-on airplane configuration.

The plots on the left in figure 3 show an entry with the pilot flying manually using the conventional control system which has acceleration reaction controls and aerodynamic damping augmentation. On the right in figure 3, the pilot is using the adaptive control system with attitude-hold modes operative. This system also has command reaction controls that are automatically blended with the aerodynamic controls.

The most significant difference between the two entries is the magnitude of the angle-of-sideslip oscillation as normal acceleration and dynamic pressure build up. The excursions are smaller and the controllability was superior with the higher-gain system. The entries were made by different pilots; however, their evaluations of the entry control tasks were similar--satisfactory, with a slight deterioration in the lateral-directional mode. At angles of attack higher than achieved during these entries, however, the controllability of the airplane with the adaptive control system is predicted on the X-15 simulator to be clearly superior.

Entry controllability with the other controls evaluated, conventional controls with stability augmentation (SAS) and reaction damping (RAS) and the adaptive rate command controls, has been rated satisfactory also by the pilots. The pilots' average rating of entry pitch, roll, and yaw controllability with the various control systems is summarized in table II. Although entry controllability with all the controls was rated satisfactory, the adaptive rate command controls were rated superior to the other controls. The conventional controls with reaction augmentation were rated least satisfactory; however, the pilots did appreciate the addition of the reaction damping. All flights to high altitude, since the addition of reaction augmentation, have been made with this system. Recent flights have been made with better-defined control objectives for the follow-on program. The pilot ratings probably reflect these control requirements. Only a limited number of entries have been made with the adaptive system hold modes; however, these control modes have been used more extensively in other phases of flight. Pilot opinion on the use of hold modes is mixed. These modes greatly reduce the pilot's concentration and workload, but some pilots prefer to be active in the control loop at all times. An acceptable compromise preferred by some is active control of the primary control mode, pitch, and the use of attitude command in roll and yaw.

The amount of control used during X-15 entries is summarized and compared to the control available in figure 4. The aerodynamic control angular acceleration used in pitch, roll, and yaw includes the critical setup period prior to dynamic-pressure buildup through pullout to a constant glide angle of attack or rate of descent. The controls used include both the pilot and the augmentation system.

A much higher percentage of available aerodynamic control was used in pitch, primarily for trim to establish and hold angle of attack, than was used in the other control modes. During the initial part of the entry, nearly 100 percent of the control available was used to initiate pullout, but as dynamic pressure increased and the pullout developed, a lower percentage of control was required. The control used in roll and yaw was low and was for stabilization. Similar requirements for stabilization in pitch were indicated. Reaction controls were used during the first part of the entry. Reaction controls with an authority of only about 1 percent of the maximum available aerodynamic controls were found to be completely satisfactory.

Since the pilot is dependent on systems for stabilization during the entry, some discussion of systems experience is in order. Many of the problems with the various control systems were solved during the design and early flight tests. Some of these, such as limit cycles, structural coupling, and overall reliability (ref. 2), have been analyzed and solutions found. Other problems were recognized, but, because they were never expected to be encountered in flight, no hardware changes were made to the airplane. However, some of the problems were encountered in flight. Typical was saturation, which led to nonlinear system instability with the high-gain adaptive system.

Early in the design of the adaptive controls it was recognized that high rate commands from the pilot could not be followed by the control-surface actuators. Servo motion would be reflected back to the pilot's stick as stick kicks, and system instability would be experienced because of the inability of the system to follow the commanded rate. For nearly 40 flights, rate-limit problems were not encountered, even during entries from the highest altitudes. However, the problem was experienced during a relatively routine flight and the airplane became uncontrollable in roll for a short time. A flight record of that experience is presented in figure 5. Roll and pitch rate exceeded the recorded limits during the maneuver, as indicated by the dashed lines. The straight segments of the time history indicate that the servo rate limit was exceeded.

The incident was initiated by a rather modest pitch control command with some roll command by the pilot. The resulting rate limiting of the servo produced sufficient system lag to reduce the pitch-damper effectiveness and to cause the roll command system to go unstable. Reduced commands and adaptive gains restored the system to operational status, and the airplane motions were again damped.

Analysis of the problem showed that the system nonlinear instability was caused by rate-limit-induced lag at low frequencies. The inclusion of a simple lag-lead circuit in the servo loop to reduce the lag at the critical low frequencies appeared promising. Simulation tests indicate that this change will result in improved controllability with little degradation in overall system performance. Incidentally, many of the control-system problems have been studied on the fixed-base simulator; however, this phenomenon was nonreproducible on the simulator until the capacity and hydraulic pressure of the hydraulic system were increased to be similar to that of the airplane.

During the design and flight testing of the X-15 airplane, simulation has been relied on more heavily than in any other airplane program. Both general and specific control problems have been investigated by use of various ground-based and airborne simulators, as illustrated in figure 6. A complete six-degree-of-freedom simulation using the cockpit and actual control hardware, shown in the center of the figure, was mechanized early in the design of the airplane. The simulator is still used for flight planning and pilot familiarization (ref. 4). Routinely, pilots have evaluated the fidelity of the simulator in comparison with actual flight. The consensus of the pilots is that the fixed-base simulation satisfactorily duplicates the X-15 instrument flight-control task. However, it is only as good as its mechanization and, thus, for realism, must be as complete as possible and must be updated on the basis of actual flight experience.

Before the flights to high altitude, the first pilots practiced entry flight on a moving-base simulator under the actual acceleration environment to determine the detrimental effects of acceleration on controllability. However, they, and pilots added to the program later, have since concluded that practice under high acceleration was unnecessary. Entry acceleration of 5g (normal) and 1g to 2g (longitudinal) had little, if any, effect on their control performance during entry.

One possible exception was the pilot-induced oscillation with the dampers-off, ventral-on configuration (ref. 5). The fixed-base simulator for this configuration, with the pilot using a special control technique, gave an optimistic indication of the controllability compared with that experienced in actual flight, since it provided no kinesthetic or outside visual cues. In this case, the acceleration environment was detrimental to control.

POSSIBLE APPLICATIONS

A comparison of X-15 entry with a simulated orbital lifting-body entry (fig. 7) shows little similarity. The X-15 entries are of much shorter duration and present a more severe control problem with the rapid buildup in dynamic pressure and acceleration than the orbital entry.

However, the X-15 entry experience does provide results that may be applicable to certain launch-abort situations and to terminal ranging to a landing for future lifting-entry vehicles. Figure 8 shows an X-15 entry from 285,000 feet and an M2-F2 simulated lifting-body entry following abort during the first-stage launch. Similar levels of acceleration are required for each vehicle pullout. Although the "wing" loading of the lifting body is somewhat greater than that of the X-15, the effect of the lower lift-drag ratio of the lifting body is larger and results in lower peak dynamic pressure during entry. Like the X-15 airplane, the controllability of the lifting body was indicated to be satisfactory with moderate gain dampers.

RECOVERY GLIDE

In addition to the entry experience with the X-15 airplane, many flights have been made to hypersonic speeds for research purposes. Several recovery techniques have been investigated. Some of these were to maintain constant angle of attack for maximum range, constant dynamic pressure for obtaining heating and other aerodynamic data, and constant rate of change of altitude for controlling range by flight-path control. These flights have been planned as straight approaches to the landing area from about 100,000 feet and a Mach number of 5. Only terminal maneuvering to the landing was required and, with the X-15 airplane, the pilots have preferred a 360° approach to landing. This approach allows the pilot to deplete excess range by bank-angle modulation.

This recovery technique will be representative of a lifting-entry-vehicle approach to the landing site from the initial conditions of 100,000 feet and a Mach number of 5. Although reaction controls may be used during the initial phase of entry at higher Mach numbers, aerodynamic controls are expected to be used for the control of airplane attitude while controlling range and approach to landing.

The aerodynamic controls used and the maneuvering required during the X-15 recovery from Mach 5 to landing is summarized in figure 9. Note that the Mach number is highest at the right, decreasing to landing speed to the left. Only small bank angles and low roll rates were used by the pilots during the stabilized high Mach number portion of the recovery. Less than 10 percent of the roll control available was used. About 40 percent of the longitudinal control available was used for trimming to the desired angle of attack for control of range.

At the lower Mach number, significantly more bank angle and roll rate were used for terminal maneuvering; however, a much lower percentage of control available was used in both roll and pitch, inasmuch as effectiveness is higher and much less control is required for longitudinal trim. From these results it can be inferred that this part of the recovery of entry vehicles will require substantially less control than conventional fighter-aircraft maneuvering, inasmuch as maneuvering is minimal except during landing approach.

CONCLUDING REMARKS

Successful piloted entries from high altitudes, the most extreme from 354,200 feet, have been accomplished with the X-15 airplane. The high steady acceleration and rapidly changing aerodynamic environment did not affect the pilot's capability to control the entry. All the control systems evaluated were judged by the pilots to be satisfactory for the control of the X-15 entry from the design altitude. The overall X-15 flight experience should be useful in assessing control requirements for future lifting-entry vehicles. Entries have been made that presented more severe control problems than predicted for entries of advanced vehicles at higher velocities.

Flight Research Center,
National Aeronautics and Space Administration,
Edwards, Calif., October 7, 1965.

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TABLE I.— SUMMARY OF HIGH-ALTITUDE EXPERIENCE

Year	Maximum altitude, ft	Control system	Configuration
1961	217,000	Conventional - SAS	Ventral on
1962	246,700	Adaptive (hold)	Ventral on
1962	247,000	Conventional - SAS	Ventral on
1962	193,600	Adaptive (rate command)	Ventral on
1962	314,750	Adaptive (hold)	Ventral on
1963	271,700	Adaptive (rate command)	Ventral off
1963	209,400	Adaptive (rate command)	Ventral off
1963	223,700	Adaptive (rate command)	Ventral off
1963	285,000	Adaptive (rate command)	Ventral off
1963	226,400	Conventional - SAS, RAS	Ventral off
1963	347,800	Adaptive (rate command)	Ventral off
1963	354,200	Adaptive (rate command)	Ventral off
1964	195,800	Conventional - SAS	Ventral off
1965	209,600	Adaptive (rate command)	Ventral off
1965	244,700	Adaptive (rate command)	Ventral off
1965	280,600	Adaptive (rate command)	Ventral off
1965	212,600	Conventional - SAS, RAS	Ventral off
1965	208,700	Conventional - SAS, RAS	Ventral off
1965	271,000	Adaptive (rate command)	Ventral off

TABLE II.— PILOT RATING OF ENTRY CONTROLS

Pilot	Conventional SAS		Conventional SAS-RAS		Adaptive		Adaptive (hold)	
	Average rating	No. of flights	Average rating	No. of flights	Average rating	No. of flights	Average rating	No. of flights
A	2.1	1	1.3	1	1.3	5	---	-
B	2	1	---	-	---	-	1.8	2
C	---	-	2.3	1	1.8	3	---	-
D	1.8	1	---	-	1.8	4	---	-
E	---	-	2.5	3	---	-	---	-
F	---	-	3.3	1	---	-	---	-
	2	3	2.4	6	1.6	12	1.8	2

X-15 FLIGHT TO HIGH ALTITUDE

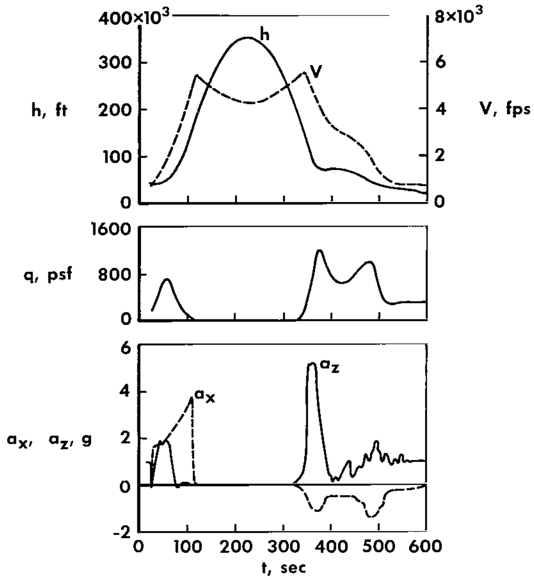

Figure 1

RANGE OF X-15 ENTRY PARAMETERS

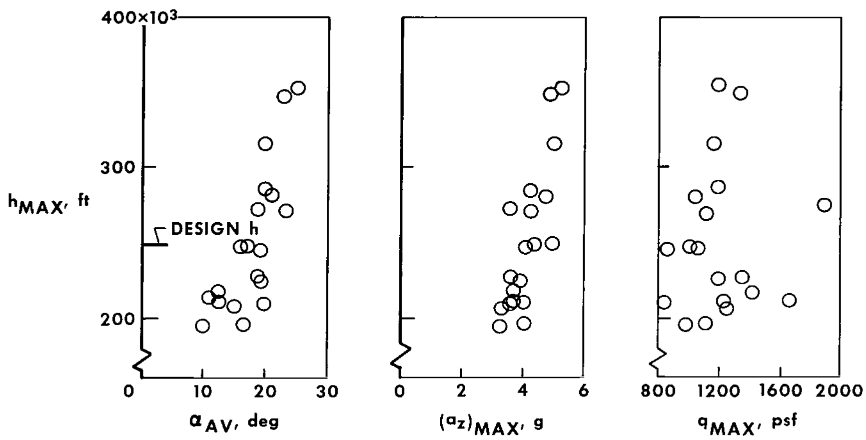

Figure 2

CONTROLLABILITY OF ENTRY FROM 250,000 FEET

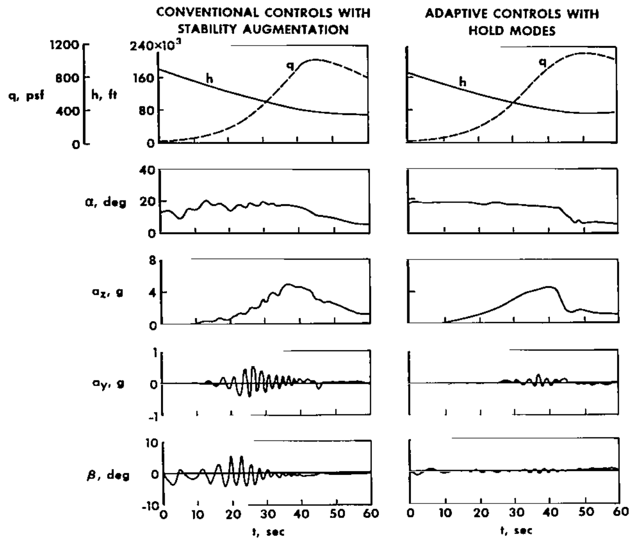

Figure 3

CONTROL UTILIZATION DURING X-15 ENTRY

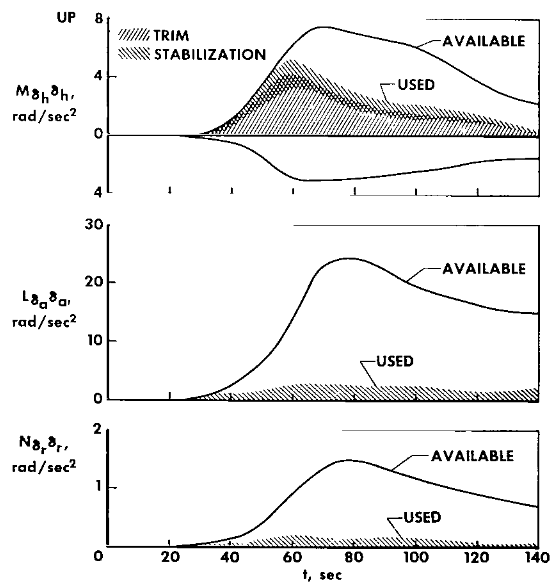

Figure 4

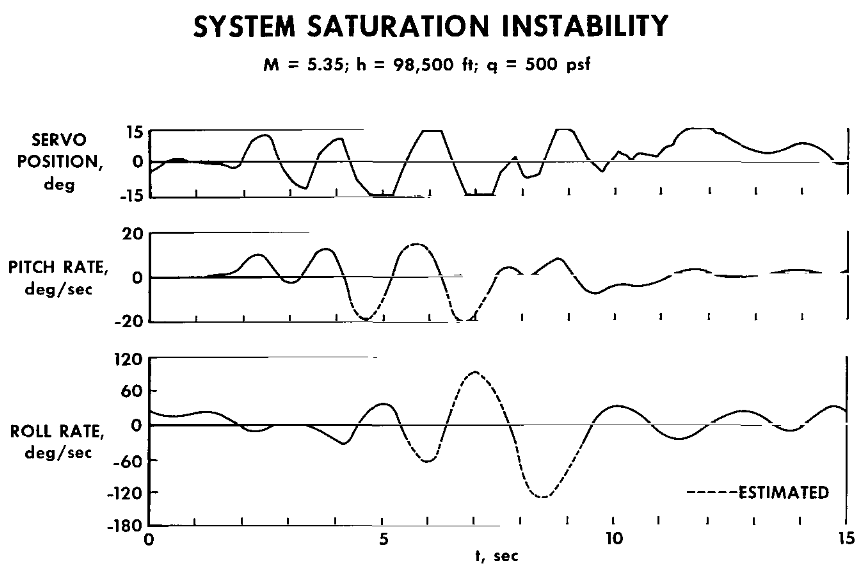

Figure 5

X-15 SIMULATORS

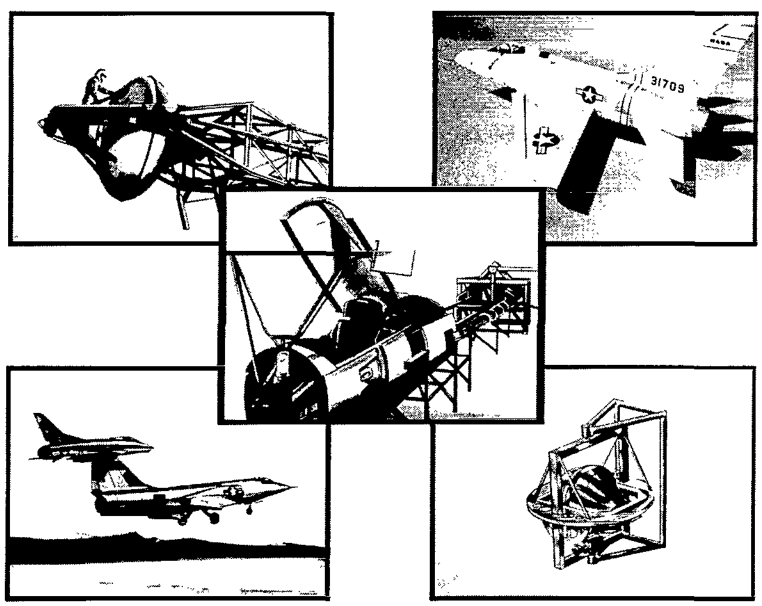

Figure 6

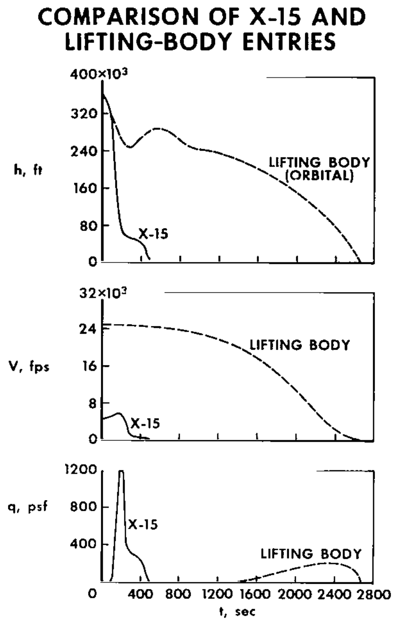

Figure 7

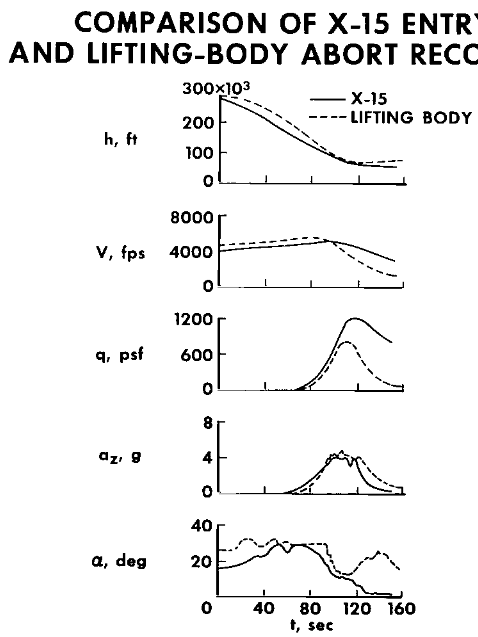

Figure 8

X-15 MANEUVERING EXPERIENCE

GLIDE TO BASE

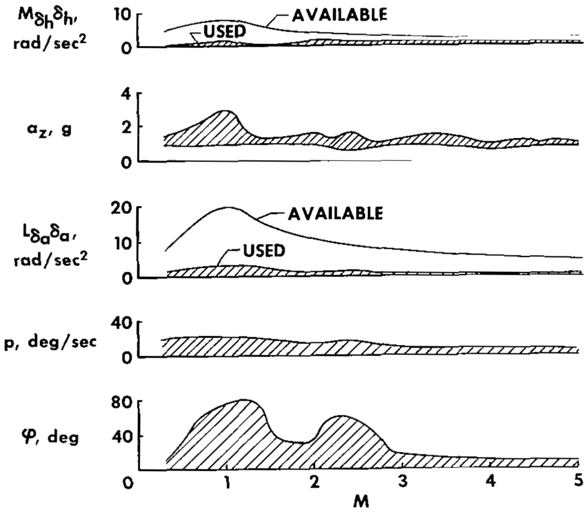

Figure 9

NASA-Langley, 1966 H-415

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