program in which flight and system operational experience can be gained pays large dividends in providing a more successful overall operation.

#### Concluding Remarks

Sixteen successful X-15 entries from high altitudes--the most extreme from 354,200 feet-have provided confidence that lifting entries can be made with higher-performance entry vehicles.

The X-15 program has offered the opportunity to assess and resolve the problems of controls, displays, and operational methods required for steep short-time entries from high altitudes. Such entries are predicted to be more severe from a controllability standpoint than entries with a lifting entry vehicle. The contact flight ranging and recovery of the low-lift-drag-ratio, high-wingloading X-15 airplane have become routine.

Although instrument flight approach and landing of lifting entry vehicles is feasible, some research effort will be required to develop operational methods and required displays.

#### Symbols

- D drag
- L lift
- q dynamic pressure, psf
- $\alpha$  angle of attack, deg

 $\theta$  pitch angle, deg

- Subscripts:
  - max maximum
  - min minimum

# References

- Love, E. S., and Pritchard, E. B.: A Look at Manned Entry at Circular to Hyperbolic Velocities. Presented at AIAA 2nd Manned Space Flight Meeting, Dallas, Tex., Apr. 22-24, 1963.
- Anon.: Flight Control Study of a Manned Re-entry Vehicle. WADD Tech. Rep. 60-695, Vols. I and II (Contract No. AF 33(616)-6204, Project No. 8225, Task No. 82182), Wright Air Dev. Div., U.S. Air Force, July 1960.
- Petersen, Forrest S., Rediess, Herman A., and Weil, Joseph: Lateral-Directional Control Characteristics of the X-15 Airplane. NASA TM X-726, 1962.
- <sup>4</sup>. Walker, Joseph A., and Weil, Joseph: The X-15 Program. Presented at AIAA 2nd Manned Space Flight Meeting, Dallas, Tex., Apr. 22-24, 1963.
- Taylor, Lawrence W., Jr., and Merrick, George B.: X-15 Airplane Stability Augmentation System. NASA TN D-1157, 1962.
- Boskovich, Boris, Cole, George H., and Mellen, David L.: Advanced Flight Vehicle Self-Adaptive Flight Control System. WADD Tech.

Rep. 60-651, Part I (Contract No. AF 33(616)-6610, Project No. 8226, Task No. 10889), Wright Air Dev. Div., U.S. Air Force, Sept. 30, 1960.

- 7. Tremant, Robert A.: Operational Experiences and Characteristics of the X-15 Flight Control System. NASA TN D-1402, 1962.
- 8. Sjoberg, S. A.: A Flight Investigation of the Handling Characteristics of a Fighter Airplane Controlled Through Automatic-Pilot Control Systems. NACA RM L55F01b, 1955.
- Cooper, George E.: Understanding and Interpreting Pilot Opinion. Aero. Eng. Rev., vol. 16, no. 3, Mar. 1957, pp. 47-51, 56.
- White, Robert M., Robinson, Glenn H., and Matranga, Gene J.: Résumé of Handling Qualities of the X-15 Airplane. NASA TM X-715, 1962.
- 11. Stillwell, Wendell H., and Drake, Hubert M.: Simulator Studies of Jet Reaction Controls for Use at High Altitude. NACA RM H58G18a, 1958.
- Cooper, N. R.: X-15 Flight Simulation Program. Paper no. 61-194-1888, Amer. Rocket Soc. and Inst. Aero. Sci., June 1961.
- Holleman, Euclid C., and Wilson, Warren S.: Flight-Simulator Requirements for High-Performance Aircraft Based on X-15 Experience. Paper no. 63-AHGT-81, Amer. Soc. Mech. Eng., Jan. 1963.
- 14. Hoey, Robert G., and Day, Richard E.: Mission Planning and Operational Procedures for the X-15 Airplane. NASA TN D-1159, 1962.
- 15. Hopkins, Edward J., Fetterman, David E., Jr., and Saltzman, Edwin J.: Comparison of Full-Scale Lift and Drag Characteristics of the X-15 Airplane With Wind-Tunnel Results and Theory. NASA TM X-713, 1962.
- 16. Matranga, Gene J.: Analysis of X-15 Landing Approach and Flare Characteristics Determined From the First 30 Flights. NASA TN D-1057, 1961.
- Weil, Joseph, and Matranga, Gene J.: Review of Techniques Applicable to the Recovery of Lifting Hypervelocity Vehicles. NASA TM X-334, 1960.
- Armstrong, Neil A., and Holleman, Euclid C.: A Review of In-Flight Simulation Pertinent to Piloted Space Vehicles. AGARD Rep. 403, 1962.
- 19. Matranga, Gene J., Dana, William H., and Armstrong, Neil A.: Flight-Simulated Off-the-Pad Escape and Landing Maneuvers for a Vertically Launched Hypersonic Glider. NASA TM X-637, 1962.
- Banner, Richard D., Kuhl, Albert E., and Quinn, Robert D.: Preliminary Results of Aerodynamic Heating Studies on the X-15 Airplane. NASA TM X-638, 1962.
- Kordes, Eldon E., Reed, Robert D., and Dawdy, Alpha L.: Structural Heating Experiences on the X-15 Airplane. NASA TM X-711, 1962.

 $|\xi| = |\xi| = |\xi| = |\xi|$ 

Euclid C. Holleman Assistant Head, Manned Flight Control Branch

> Elmor J. Adkins Head, Systems Analysis Section

NASA Flight Research Center Edwards, California

# Introduction

Although the X-15 was not designed to investigate the problems of orbital lifting reentry, 1,2 it is the first research vehicle capable of piloted flight outside the sensible atmosphere and of lifting entry. Because its speed capability is much lower than that of orbital vehicles, the X-15 enters much more steeply, which results in shorter entry time (fig. 1) and, in some respects, a more severe entry. The steeper the entry, the more rapid will be the changes in important control parameters. This resulted in a formidable task for the X-15 design engineer and a rather severe control task for the pilot, particularly in abnormal or emergency conditions. In fact, the X-15 entry may prove to be more severe than the entry of lifting orbital vehicles. The entry research potential of the X-15 can best be illustrated (fig. 2) by comparing the X-15 velocity with that of an orbital lifting entry vehicle with similar characteristics: a lift-drag ratio of 1 to 2 and a wing loading of 75 psf. As shown, the X-15 flight envelope adequately covers the altitude and lower speed range.

Piloting experience has been obtained with the X-15 in regions of essentially zero dynamic pressure and regions of high dynamic pressure, up to about 2,000 psf. Inasmuch as the Mercury program has supplied significant control data at zero dynamic pressure, this region will not be considered in this paper. Control in regions of low and high dynamic pressure will be discussed and, based on this experience, the control-system requirements for lifting entry will be suggested. Also, the operational experience obtained during terminal guidance, navigation, and landing of the X-15, which should be applicable to lifting entry vehicles, will be discussed.

# X-15 Control Systems

More than 90 research flights have been made with the X-15 airplane using four variations of reaction controls and three types of aerodynamic controls and two airplane configurations--ventral fin on, and lower ventral fin off. When the original ventral-fin-on configuration exhibited undesirable augmentation-off control characteristics, the lower fin was removed. This resulted in a somewhat lower directional stability but, more important, a configuration controllable by the pilot throughout the flight envelope with the . damping augmentation inoperative.<sup>3,4</sup>

Sixteen X-15 flights have been made to high altitudes during which low dynamic pressures were experienced and entries were required for recovery. Altitudes up to 354,200 feet have been reached, with apogee velocities of about 4,500 fps. Entry angles of attack as high as 26°, recovery normal accelerations to 5.5g, and dynamic pressures of 1,500 psf were obtained. Two of the X-15 airplanes were equipped with conventional aerodynamic control systems with three-axis stability augmentation.<sup>5</sup> The other airplane had an adaptive rate command control system, the Minneapolis Honeywell-% control system.<sup>6</sup>

Each airplane has reaction jets for control at low dynamic pressure. The X-15 reaction controls were designed to be used only when the aerodynamic control surface effectiveness is not sufficient to maintain the desired vehicle attitude. The basic system commands a roll acceleration of 5 deg/sec<sup>2</sup>, and pitch and yaw accelerations of 2.5 deg/sec<sup>2</sup> for each of two systems. The X-15 system is completely dualized to provide the requisite fail safety for man-operated vehicles.

### Reaction Controls

Four types of reaction control systems have been used on the X-15 in high-altitude flights. The basic reaction control system is a pure thrust command system, but with thrust proportional to stick deflection outside of a dead zone of 15 percent of stick travel. An abrupt step in controlstick force of about 2 pounds is provided at about 50-percent stick deflection in pitch to provide a feel detent for the pilot at approximately onehalf the maximum reaction control thrust. The rocket motors are commanded through a separate side-located three-axis controller.

The basic reaction control systems for the X-15 airplanes have been modified to include reaction rate damping, which provides a second type of system. Electronic switching is used to provide rate damping signals for stabilization only when rocket thrust is not commanded by the pilot. One flight has been made with this system.

Two types of reaction control are available to the pilot with the MH-96 control system: a rate command reaction control for manual control and an attitude hold control loop. These control loops have been used on many of the high-altitude flights. This system also features controls-blending on the same control stick. The controls-blending is a function of aerodynamic control effectiveness and occurs only when the aerodynamic controls do not provide the airplane response required by the augmentation system or by pilot command. The automatic blending switching is accomplished by the gain changer. When all three axis gains reach 80 percent of maximum, the reaction controls are activated. The reaction controls are deactivated when all the gains reach 60 percent as the airplane enters aerodynamic flight. The reaction controls are not used until required; however, the pilot does not directly fire the attitude rockets, since his control stick commands airplane rate.

The rate command system has a dead zone of about 1 deg/sec. This design allows drift rates up to this value. The attitude hold loop is designed to hold attitude to within 2° during zero dynamic pressure.

# Aerodynamic Controls

Airplane designers have long sought a control system that would provide acceptable control characteristics, without excessive variation, over the flight envelope of the vehicle being designed. Of course, the design task becomes increasingly difficult for the entry-vehicle designer because of the expanded flight envelope. Even the definition of an acceptable system is not always clear. Yet, based on present experience and predicted future requirements, attempts are being made to design acceptable control systems for the future vehicles.

Basic aerodynamic controls. Aerodynamic control<sup>7</sup> is provided in the X-15 through conventional aerodynamic surfaces using vertical surfaces for yaw control and the horizontal tail for both pitch and roll control. All the aerodynamic control surfaces are actuated by irreversible hydraulic systems. Control force is provided by bungee for pilot feel. A conventional center stick and rudder pedals are used for aerodynamic control; however, a side-located control stick for pitch and roll control is provided for use in high-acceleration environments at the option of the pilot. Although the aerodynamic and reaction controls are blended with the aerodynamic control sticks on one of the X-15's, the other two airplanes have a separate three-axis controller for the reaction controls.

Stability augmentation system (SAS). To provide adequate handling qualities over the operating envelope of the X-15 airplane, damping augmentation about all three axes is necessary. Two systems that provide augmentation--the stability augmentation system and the adaptive control system--are being flight tested.

The stability augmentation system<sup>5</sup> provides auxiliary aerodynamic damping by actuating the aerodynamic control surfaces to oppose the rotational velocity of the airplane. Unique features of the system are the cockpit gain selection and the inner connection required for operation of the left and right horizontal stabilizers which provide both pitch and roll input. The gains used for most of the flights were 0.6 deg/deg/sec in pitch, 0.3 deg/deg/sec in roll, and 0.24 deg/deg/sec in yaw. For the ventral-on configuration, a yaw-rate signal was fed into the roll channel with a gain of 0.54 deg/deg/sec. This system does not provide attitude stabilization.

A large damper authority is required to provide adequate auxiliary damping throughout the aerodynamic portion of the flight envelope. The system was designed to have the same authority in pitch and yaw as the pilot and twice the pilot's authority in roll. With large authority, a reliable, fail-safe system is mandatory. To achieve this feature, the dual-channel concept of a working channel and a monitor channel was used. If the channels do not agree within specified limits, the system is automatically disengaged.

MH-96 system. X-15 flights to high altitude have been made with the conventional system previously discussed and with a more advanced system, the MH-% adaptive control system.<sup>6</sup> Some of the features of the system are: self-adaptive gain changing, rate command control, automatic trim, acceleration limiting, hold modes, automatic blending of aerodynamic and reaction controls, control-stick steering, and improved reliability and fail safety. These features and the flight tests of the system will be discussed briefly in an attempt to indicate the aerodynamic controls that will be required for lifting entry vehicles. The adaptive system design goals of independence from configuration characteristics and gain scheduling for a particular flight environment should be appropriate for all future vehicles.

The design concept of the MH-96 adaptive control system is shown in figure 3. Control commands are introduced to the hydraulic actuators through conventional mechanical inputs and simultaneous electrical inputs to the model. The system operates on the principle of using sufficient lead in series with a high forward loop gain so that the response of the aircraft will be approximately the response of the model. This will occur if the system response is 3 to 5 times faster than the airplane response.

The self-adaptive gain-changing feature of the MH-96 adaptive control system maintains high gains in an attempt to follow the model and, during operation in reduced dynamic pressure regions, activates the reaction controls. By design, the system has dual channels in each axis so that if one channel fails the gain changer compensates to the limit of its gain range, thus providing nondegraded performance for some single failures. This feature is very desirable for the X-15 because of the rapid changes in the operational environment of the airplane.

The use of the rate command control feature of the adaptive system results in a number of unconventional flying qualities,<sup>8</sup> in that the airplane no longer returns to the trimmed angle of attack. Rate command trim is also used and is an obvious companion to rate command control.

Because the X-15 augmentation servo has limited control authority, automatic trim is used to provide full surface authority for the adaptive system by energizing the trim actuator so that the servo is permitted to operate about its center position for all flight conditions. However, the automatic trim would not be required if a fullauthority servo were used in the system.

Normal-acceleration limiting is a design feature of the X-15 control system that limits the entry acceleration to a desired preset value.

Outer-loop pitch angle, angle of attack, bank angle, and heading hold modes are a part of the system. These modes have been used on many of the extreme flights to enable the pilot to obtain more precise flight data.

The control-stick steering mode of the adaptive system was designed to allow the pilot to alter the hold attitude during hold-mode operation. This mode, however, has not been used as intended, since the pilot can overpower any of the automatic modes in the system. As a result of the adaptivesystem modes, control-stick steering is probably

HOLLEHAN-2-

the least appreciated by the pilots.

For the X-15 application, extremely high reliability is a requirement because of the low probability of a successful entry from high altitude without augmentation. Fail safety is equally important, since a large transient in a highdynamic-pressure region would result in the destruction of the airplane. The redundancy configuration selected provides the generally incompatible objectives of reliability and fail safety. Complete dual damper channels are provided. The adaptive feature permits one channel to be lost with little or no loss in system performance. The gain computers are interlocked, when operative, to prevent overcritical gain following a limit-cycle circuit failure and to provide the desired limiting effect for hard-over failures. For model or other failures, conventional monitor circuits disengage both channels when required. This problem, combined with the NASA desire for increased flexibility, led to the incorporation of a fixed-gain damper system as a final backup system.

# Contributions to Entry Technology

### Entry Control Experience

ł

The flexibility of the X-15 operation and the number of control systems available for evaluation have provided valuable flight experience which should be applicable to the design of future vehicles. Flight data have been obtained with attitude and rate command control systems and with attitude hold modes over a wide range of altitudes and dynamic pressures of interest.

Reaction-control experience. Flight experience at low dynamic pressure during entry has been obtained with four reaction control systems: a simple acceleration or thrust command control system, acceleration command with rate damping, a rate command system, and the rate command system with hold modes. For the piloted control system, of equal importance are the effectiveness of the system configuration and the control fuel used during the control task. Figure 4 presents the low-dynamic-pressure portion of two X-15 entries from high altitudes with the pilot utilizing the acceleration command reaction control system (fig. 4(a)) and the rate command reaction control system (fig. 4(b)). Entry dynamic-pressure buildup to 600 psf is shown. The control tasks were similar. The pilot was asked to hold the heading angle to the desired value, the bank angle to zero, and the pitch angle constant until angle of attack equaled 20°, and then to hold angle of attack constant.

The pilot's inputs for the manual acceleration command control system are characterized by pulsetype operation. Although the rocket thrust response is proportional outside of the deadband, this feature of the system has not been used nor appreciated by the pilots. They disliked the deadband in the system because it made precise control difficult. With the manual system, piloting technique is all important for reasonable reaction control fuel consumption.

Although both control tasks were rated as satisfactory by the pilots (based on the Cooper scale<sup>9</sup>), it is apparent that the airplane motions in the low- and high-dynamic-pressure regions for the rate command system are controlled much nearer to the desired values. The pilot ratings, reaction control fuel used, and the dynamic pressure at which the pilot last used the reaction controls, which is an important consideration in fuel consumption, for these entry control tasks were:

	Acceleration command (fig. 4(a))	Rate command (fig. 4(b))	$\overline{\ }$
Pilot rating	Satisfactory (3)	Satisfactory (2)	
Fuel used	63 pounds	24 pounds	
Dynamic pressure at last pulse	330 psf	180 psf	

For this flight (fig. 4(b)) the pilot did not choose to control the heading during entry, and the rates developed during the oscillation were slightly less than the deadband threshold of the MH-96 reaction control system. The motions were, however, damped by the aerodynamic damping system as dynamic pressure increased.

The reaction controls were used to much higher than expected dynamic pressures in these entries. An experienced pilot can use the manual thrust command effectively to damp airplane oscillations that tend to persist at low dynamic pressures. These oscillations would, of course, be damped by an augmented or rate command system. It appears that the pilot was using the acceleration command controls to high dynamic pressure for this purpose (fig. 4(a)). From a piloting standpoint, reaction damping augmentation is especially desirable in regions of low dynamic pressure. The X-15 acceleration command reaction control systems have been modified by adding rate damping. On the one flight  $\smallsetminus$ that has been made with the system, it performed satisfactorily.

Although the entry experience with the reaction control systems has been limited, the reaction control fuel usage has been recorded and trends are indicated that may be of interest. Piloting and simulator experience is all important when considering fuel used to accomplish a control task with the manual thrust command reaction control system. With this system, fuel usage has been relatively high, in fact, higher than designed for. The reaction control fuel capacity required for the stabilization and angle-of-attack setup for entry control tasks was determined during simulated flights of the X-15 design altitude (250,000 ft) mission. During early altitude flights, it became apparent that more fuel was being used by the pilot than anticipated. Thus, a fuel transfer system was designed to enable the pilot to transfer fuel from the engine fuel-pump source to insure adequate reaction control fuel. Average fuel consumption has been about 90 percent of the design value, and on 40 percent of the entries usage was higher than predicted.

Flights with the MH-96 rate command system (fig. 4(b)) have indicated that this system will be much more effective than the manual control system for control and stabilization during operation in a low-dynamic-pressure environment. However, with the rate command system, drift rate below the threshold level of the system can result in unwanted excursions in vehicle attitude. Control fuel, it appears, will be less than required for  $H_{CLUBMAL-}$ 

#### the manual thrust command system.

Flights to high altitude using the various attitude hold features of the MH-96 reaction control system resulted in precise control and somewhat less reaction-control fuel consumption than with the manual reaction control system. The pilots have appreciated the reaction hold modes, especially in the secondary control modes such as roll.

The reaction controls have been used to much higher dynamic pressure than the value at which the effectiveness of the aerodynamic and reaction controls is equal. This value for the X-15 entry is approximately 50 psf to 75 psf. In some instances, dynamic pressures as high as 400 psf to 500 psf were reached before the pilot switched to aerodynamic controls. This operational technique has contributed to the high fuel consumption. Use of the reaction controls to high dynamic pressures may result from the rapid buildup in dynamic pressure that is peculiar to steep entries.

With manual reaction controls some of the excess fuel consumed has been used effectively by the pilot as a damping device. This has been true especially in yaw where rapid, precisely timed inputs of the rudder control were impossible with the rudders but could be accomplished easily with a hand controller.

SAS experience. The stability augmentation system has provided satisfactory control for the pilot throughout the aerodynamic flight envelope of the airplane; 10 however, the development of the system was fraught with problems. The dampersystem reliability 7 was poor early in the program. Since the recovery from high altitude was doubtful with the augmentation inoperative, a backup damping augmentation system was designed and installed in two of the X-15 airplanes. When studies indicated that the airplane would be more controllable with the lower ventral fin removed,  $^3$  this configuration change was made so that the flight program could continue while the backup damper system was being designed. Other system modifications were made to avoid structural coupling with the lightly damped horizontal-tail surfaces<sup>5</sup> and limit cycles at high aerodynamic gains. The system was designed with the flexibility of manual gain changing, which allowed versatile flight planning for research purposes. Entries have been made with the system from altitudes of approximately 250,000 feet (fig. 4(a)).

MH-% experience. Except for specific flight tests to investigate the operation of the adaptive control system with portions of the system deactivated, all flights have been made using the complete adaptive control system, which includes the automatic gain changer. The gain changer sets the channel gains as high as possible, avoiding objectionable limit-cycle amplitudes. The limit cycle results from the nonlinearities of the X-15 control-system hardware and must be designed around. The pilots have rated the adaptive mode of control as excellent. The system provides positive control and good airplane damping throughout the aerodynamic flight envelope of the airplane, including entry flight.

Although there was some speculation among pilots and designers on the acceptability of the

pitch-rate command control system, pilots have had no problem adapting to this type of system for any phase of the altitude flight from zero dynamic pressure to landing. The loss of the speed stability of the airplane has been noted by the pilots especially during the glide to the landing site when attention is required outside of the cockpit. Pitch-rate trim has been accepted only as a byproduct of the system mechanization. With this trim, an extra display quantity--the longitudinal control surface position--was desirable since the surface position is not related to the cockpit trim control position.

By means of the hold modes available to the X-15 pilot, an entire altitude flight, except for landing but including entry, can be flown automatically by resetting the hold modes to the desired values during specific phases of the mission. With the rapid changes that occur during the X-15 flights, little time is available to set the hold modes accurately. Often, when there was insufficient time to correctly trim to the desired hold attitude, the pilots have overpowered the system. Some pilots have preferred to fly the prime control quantity, pitch attitude, for example, and allow the system to hold bank angle and heading. By design, the bank angle is held to zero if the hold mode is engaged when the bank angle is less than 7°. Thus, this mode does not require a precise set-in of the desired quantity.

The automatic trim provides full surface authority for the adaptive system. This is especially desirable in low-dynamic-pressure regions, and the pilots have appreciated the increased damping. For the short entry times of the X-15 airplane, it has not been possible to assess the effectiveness of the full surface authority of the system for trim at low dynamic pressures. However, for longer-time entries, this feature should be much more important in conserving reaction control fuel.

The pilots consider the normal-acceleration limiter to be a highly desirable safety feature because the acceleration required for entry approaches the airplane structural acceleration limit. For more extreme entries than have been flown in the program, the acceleration-limiting feature would be necessary since higher accelerations would be required for longer periods of time for recovery.

The X-15 adaptive system has been very reliable. Only one component has failed in flight during 2 years of operation, which includes 21 flights covering a wide portion of the flight envelope. This failure did not degrade the performance of the system, but caused a small bias in yaw that was detectable by the pilot as only a slight directional mistrim. In 850 hours of total operating time on the flight system, only seven component failures have occurred, and five were the result of human error. This enviable reliability record can be attributed to good design and solid-state electronics. The system was designed and built around 1958-59 state-of-the-art components; thus, subsequent improvements should make future systems more reliable. Failures resulting from human error, however, will still present problems.

HOLEMAN - 4

# Ertry Control Requirements

Reaction controls. What are the features in a reaction control system that will enable the pilot to control effectively during entry? All of the X-15 pilots have endorsed the controls blending of aerodynamic and reaction controls activated by the same controller. The proportional-thrust command reaction control has not been appreciated by the pilots, nor have they used the control as a proportional control device.<sup>11</sup> In all instances, it has been used as an on-off control. The use of rate command reaction controls resulted in much more precise control and, apparently, consumed less fuel. The reaction augmentation was appreciated by the pilots. For entries of the type considered herein, the pilots have used reaction controls to dynamic pressures several times higher than expected. This resulted in the use of more reaction control fuel during several entries than predicted or designed for. The deadband design of 15 percent of stick deflection was considered to be excessive by the pilots.

Aerodynamic controls. A careful examination of the flight records when the adaptive control system was used indicates that the fully adaptive gain-changer feature of the X-15 system may not be required for many flight regimes. Recognizing that the simplest system may be the best, a study was made utilizing the complete six-degree-of-freedom X-15 simulator and a breadboard adaptive control system which could be altered as desired. The rate command system at various forward loop gains with model following and reaction-controls blending was used to investigate the controllability of the X-15 during entries from 360,000 feet. The pilot's task was primarily a pitch-axis task in which he was to hold an angle of attack of 25° until the normal acceleration reached about 5g, then hold 5g until level flight was attained. Sideslip and roll attitude were to be held as close to zero as possible. These entries (fig. 5) show very little difference in the pilot's ability to perform the maneuver, except for the entry at the lowest gain setting. In this entry, larger deviations occurred in all three controlled parameters. The pilot felt that excessive and continuous attention was required at the lower gain, whereas the moderate-gain and adaptive-gain entries were almost equally acceptable. These simulated entries compare well with an actual flight entry from 354,200 feet (right side of fig. 5) in which the adaptive control system was flown manually by the pilot.

The results of this study are summarized in figure 6 in terms of pilot opinion of the entry control task for each of the systems investigated. From these data it is apparent that successful entries can be accomplished with either of the systems and that acceptable piloting performance and ratings are obtained with the moderate fixed-gain rate command system. It is interesting to note that the pilot ratings for actual flight are somewhat better than those for the simulator tests. Also, the pilot stated that controlling the airplane was somewhat easier in flight than on the simulator because of the additional visual and motion stimuli available in flight and the better mechanical condition of the airplane control system.

It should be remembered that the X-15 entry is severe from the standpoint of rate of change of parameters and that it is conceivable that even . systems with lower gains may be acceptable for higher-performance vehicles with longer-time entries. Certainly, the fixed-gain concept should be considered for manual control.

Some of the controls which have contributed to the success of the X-15 program may not be required for the orbital lifting entry vehicle, for example, the adaptive gain changer, which initially prompted the adaptive design concept. Perhaps the most important reason for including the gain changer would be for fail safety. With this feature, certain system failures may occur without degrading system performance. For lifting entry vehicles, however, the pilot may have time to recognize such system malfunctions and switch to backup modes, by virtue of the longer entry time available. It is of interest to note that present design trends appear to be toward the triply redundant system, which also would eliminate the need for the gain changer for fail safety.

The rate command control can provide satisfactory control and damping over the wide range of aerodynamic characteristics from orbital speed to landing and, so, appears to be the logical choice for the primary control system of a lifting entry vehicle. The companion rate trim has not been so widely accepted, but, if properly mechanized, will provide acceptable trim. Full utilization of the capabilities of the pilot or pilots would probably remove the requirement for automatic trim, since some member of the crew could monitor this quantity during the long entry times. Similarly, the acceleration-limiting feature may not be required; the onset of acceleration for these entries will be much slower than in the X-15 entry. During certain abort situations, however, acceleration limiting may be desirable. Detailed studies of the mission and abort situation will be required to define the desired acceleration limiting.

Hold modes will certainly be desirable to reduce crew workload during the entry and perhaps provide more precise control of flight path for energy management and aerodynamic-heating considerations. Automatic switching of aerodynamic and reaction controls may not be required, inasmuch as time will be available for manual switching. By monitoring such factors as control effectiveness and reaction control fuel consumption, it should be obvious when switching is required.

Reliability and fail safety will be as vital in the design of this system as in the X-15 adaptive system, however, in a somewhat different manner. Design reliability must be based on much longer operating time for a mission, but perhaps for fewer missions. Fail-safety philosophy applied in past manned-system designs should be adhered to.

# Entry Simulation

In preparation for the X-15 program, several simulation programs<sup>12,13</sup> were conducted to prepare the pilots for the extreme altitude and speed missions of which the X-15 is capable. As the program has progressed, the six-degree-of-freedom fixed-base simulator has been relied upon heavily for many operational aspects. The simulator has been used by the pilots to practice each flight.<sup>14</sup> Thus, as a by-product of the program, data have been obtained that aid in defining the simulator

requirements for high-performance airplanes. After X-15 flights, the pilot's opinions of the entry control task in flight and on the fixed-base simulator have been compared. Such a comparison is presented in figure 7. As expected, controllability was rated slightly higher in flight than on the fixed-base simulator. None of the kinesthetic cues of flight are duplicated on the simulator, and, of course, there is greater motivation in flying the actual airplane. However, the mechanics of the entry control task on the simulator were rated similar to the flight control task.

The initial X-15 pilots were exposed to the entry control task on a moving-base simulator which duplicated the entry acceleration environment. Although the pilots did not feel it was necessary to prepare for each X-15 flight in this manner, exposure to the expected acceleration did give them confidence that they could perform the control task under the acceleration environment. The performance of pilots with and without the centrifuge experience, however, has been equally acceptable.

# Navigation and Recovery

Ranging and navigation. As important for safe recovery as the control of vehicle attitude for stabilization during entry is the control of the rate of dissipation of energy, or control of the range of the vehicle. Although ranging is not the problem with the X-15 that it will be with the orbital entry vehicle, similar energy-management controls must be exercised by the X-15 pilot for successful recovery of the vehicle after atmospheric entry.

For high-altitude X-15 flights requiring entries for recovery, the maximum range from launch to landing has been about 280 miles, which occurred on the highest altitude mission made to date. To illustrate the range capability  $^4$  of the airplane, several entries were flown on the simulator. During steep, short-time entries, the modulation of lift-drag ratio has very little effect on range until recovery to level aerodynamic flight is achieved (fig. 8). During pullout to level flight, the pilot controls range by modulating the vehicle lift-drag ratio or by turning flight. Certainly, cockpit display of the range capability of the vehicle during entry will be required for orbital lifting entry vehicles. Such a display has not been necessary in the X-15; however, a mechanization is planned for future use by the X-15 pilots.

The X-15 flights have been planned conservatively.<sup>14</sup> A ground controller monitors the flights and, with precomputed range tracks and flight radar range data, suggests flight-path control changes to assure safe ranging of the airplane following an entry. By plan, all flights have been VFR. Although much of the research information requested must be obtained by flying a precise instrument flight plan, terminal ranging has been by visual piloting. Of course, it is the pilot who must judge finally on the attitudes and configurations flown. Missions are planned and practiced to acquaint the pilot with all flight-plan variations likely to be encountered in flight. The pilots have indicated that they can see the landing site under the VFR conditions and can identify the site from the maximum altitude attained, 350,000 feet, and from a range of 160 miles.

÷.

The X-15 entries have been planned with some 80 to 100 miles excess range during the nonaerodynamic phase of flight and some 40 to 60 miles excess range in the aerodynamic phase (fig. 9). By modulating flight path and lift-drag ratio, the pilots have had no difficulty arriving over the landing site at a nominal high key of 20,000 feet and a Mach number of 0.8. The operational envelope of the X-15 flights (crosshatched area) is compared to the minimum range required to return to Edwards (solid line). On only one occasion has the recovery been marginal (dashed line). In this situation, the pilot, engrossed in checking onboard systems, ballooned slightly during pullout and nearly overflew the landing site. But, with a call from the ground monitor, he performed a steep turn and was able to land on the south end of the lake rather than on the north lakebed as planned.

Key factors in the control of range have been angle of attack and speed brakes. By flying the angle of attack for maximum lift-drag ratio, the pilot can achieve maximum range; by modulating speed brakes and by turning flight, minimum range is obtained. Although the effectiveness of the speed brakes (which have a drag increment15 approximately equal to the  $\alpha = 0^{\circ}$  drag of the vehicle) in reducing range is considered to be satisfactory by the pilots, they have expressed a desire for more flexibility in the operation of the brakes. The present brake system is relatively slow acting, about 5° of brake deflection per second. This results in a rate of change of drag coefficient of about 0.01 per second or an increment in lift-drag ratio of about 0.2 per second. A faster-acting speed brake, particularly in closing, would allow more precise control of range in the approach to landing. A speed-brake closure rate twice as rapid as the present rate is desired by the pilots. In addition to being used as a range-control device, the speed brakes have been used to increase the directional stability of the airplane in flight attitudes where the level of stability was critical. Also, they have been used to modulate overall performance during engine operation to enable the pilots to obtain more precise flight research data.

With the X-15, there have been no ranging and recovery problems in operating VFR. Terminal navigation has been by contact flight with ground monitoring. IFR entry and VFR recovery require only a clear-weather recovery area of about 200 miles around the intended landing site. This has been the usual mode of operation of the X-15, inasmuch as the entire altitude flight plan requires instrument flight through atmospheric entry. The pilot then navigates VFR to arrive over the landing site at the desired high-key position for approach and landing.

Approach and landing. Successful recovery of an entry vehicle requires a safe landing at the desired landing site. In 1958, a program was initiated specifically to determine a satisfactory technique for accurately and repeatedly landing low-lift-drag-ratio airplanes, 16, 17 in particular, the X-15. The low lift-drag ratio and high wing loading of the X-15, for example, combine to produce, in the landing approach, one of the most challenging aircraft to land.

Since the steep approach of entry vehicles has defied successful ground-based simulation, a flight program was conducted with airplanes having similar characteristics. This program proved to be of great value to the X-15 pilots in acquainting them with the approach and landing expected of this class of vehicles. Now, after many landings, this phase of the flight has become routine and spot landings are requested of the pilots. These requests serve two purposes: they help to prepare the pilots for emergency landings, and they provide data on the landing requirements for future vehicles. Touchdown dispersion with the X-15 is shown in figure 10. Touchdown has occurred within ±2,500 feet of the desired zero point, and 70 percent of the non-emergency landings have occurred within ±1,000 feet of the desired point. Slideout, shown also on figure 10, has ranged from about 4,000 fect to 8,700 feet. Although the pilot has little directional control of the X-15 below 100 knots, lateral slideout has nominally been about 200 feet, but values as high as 2,000 feet have been recorded for crosswind landings on a damp lakebed. However, with effective nosewheel steering, it appears that low-lift-drag-ratio gliders with speed brakes for drag modulation could be X-15 landed successfully on 2- to 3-mile runways. touchdown vertical velocity has averaged 3.4 feet per second, with a range of 0.5 to 9.5 feet per second.

Most of these approaches have been from a high-key position of 20,000 feet and a Mach number of 0.8, with a circular overhead approach pattern.<sup>16</sup> This type of pattern<sup>18</sup> has been preferred for visual landing approaches, as all of the X-15 approaches have been. The straight-in approach has the advantage of reducing pilot judgment requirements, since only drag modulation is necessary to insure the proper airspeed. Instrument approaches with lifting entry vehicles may require straight-in approaches or perhaps some technique not yet developed. Certainly, new displays will be required for these steep, high rate of descent IFR approaches and high landing speeds.

Of somewhat more importance for the lifting entry vehicle than for the X-15 airplane is the external visibility required to land vehicles with low lift-drag ratios and high wing loadings, 19 since the problems of heat protection will be much more complex than with the X-15. The X-15 pilot has 180° of peripheral vision and about 17.5° of forward vision, 10° up and 7.5° down. With this field of vision and with the assistance of an escort airplane, the X-15 landings have become routine. Actually, in the landing attitude the pilot's downward vision is limited to about 0° by airplane attitude. Two landings have been made with reduced vision on one side when the cockpit glass shattered as a result of aerodynamic heating. For one of these landings, the entire side glass panel was opaque.

#### Aerodynamic Heating

Only a cursory treatment of the aerodynamicheating results that have been obtained during the X-15 program will be presented in this paper. More complete data are included in references 20 to 23. Although aerodynamic heating has not been a problem on any of the X-15 entries, by virtue of the design temperature of 1,200° F, predictions of aerodynamic heating on the airplane have been made for each of the altitude entry missions. The temperatureprediction process developed for this program involves three digital computer programs. First, the local flow is computed for the conditions expected during the flight. The computed local flows are used to calculate the aerodynamic heat transfer to the airplane surfaces. Then, the differential equation describing the timedependent heating of the thin-skinned areas is integrated to give skin temperature as a function of time during the flight. Finally, the aerodynamic-heating inputs are used to calculate the transient heating of internal structural areas where heat transfer is by conduction and/or radiation.

Figure 11 compares the calculated and measured wing temperatures during an X-15 altitude flight to 315,000 feet. The prediction methods now being used were arrived at by using empirical coefficients developed to modify the basic theoretical calculations and improve the actual prediction process. The X-15 entries made to date are not temperature-limited, as orbital entries would be expected to be; however, temperature-prediction methods for the X-15 appear to be acceptable and should provide additional insight into the aerodynamic heating of the orbital entry vehicle.

#### Additional Contributions of the X-15 Program

In addition to the operational contributions to entry technology already discussed, the X-15 program has made many other contributions, although perhaps more subtle. For example, at least up to Mach numbers of 6, the measurement and prediction methods used to determine the stability and control derivatives<sup>24</sup> of complicated configurations have been verified with actual flight-determined derivatives. Both pilots and designers have gained increased confidence in the methods of predicting handling qualities and the levels of stability required at hypersonic speeds. All of the maneuvers required of entry vehicles have been performed by the X-15 pilots, using a side-located controller, in an acceleration environment as hostile as would be expected during orbital entry.

Airplane systems<sup>25</sup> have been designed and made to function in all of the environments that will be operational for the lifting entry vehicle. Pilots have proved that the human can control effectively in many flight regimes from zero g to high g. For the X-15 program, the pilot was integrated into the design far earlier and more completely than with any previous design. The success of this program attests to the wisdom of including the pilot in a program at its beginning.

Although the degree of aerodynamic heating at some locations on the airplane was predicted, other locations sustained heat damage during routine flight. Locations such as landing-gear doors require much better seals than originally believed. Also, skin or structural junctures where the boundary layer was tripped resulted in much higher heat loads, sometimes buckling the skin.<sup>21</sup> Skid-type landing gear<sup>26</sup> proved satisfactory; however, this type of gear, it appears, required a new design criteria because of the radically different rebound reaction loads that are experienced with the gear in this rearward location.

Finally, the X-15 program has demonstrated that an incremental-performance-buildup flight

program in which flight and system operational experience can be gained pays large dividends in providing a more successful overall operation.

#### Concluding Remarks

Sixteen successful X-15 entries from high altitudes--the most extreme from 354,200 feet-have provided confidence that lifting entries can be made with higher-performance entry vehicles.

The X-15 program has offered the opportunity to assess and resolve the problems of controls, displays, and operational methods required for steep short-time entries from high altitudes. Such entries are predicted to be more severe from a controllability standpoint than entries with a lifting entry vehicle. The contact flight ranging and recovery of the low-lift-drag-ratio, high-wingloading X-15 airplane have become routine.

Although instrument flight approach and landing of lifting entry vehicles is feasible, some research effort will be required to develop operational methods and required displays.

#### Symbols

- D drag
- L lift
- q dynamic pressure, psf
- $\alpha$  angle of attack, deg

 $\theta$  pitch angle, deg

- Subscripts:
  - max maximum
  - min minimum

# References

- Love, E. S., and Pritchard, E. B.: A Look at Manned Entry at Circular to Hyperbolic Velocities. Presented at AIAA 2nd Manned Space Flight Meeting, Dallas, Tex., Apr. 22-24, 1963.
- Anon.: Flight Control Study of a Manned Re-entry Vehicle. WADD Tech. Rep. 60-695, Vols. I and II (Contract No. AF 33(616)-6204, Project No. 8225, Task No. 82182), Wright Air Dev. Div., U.S. Air Force, July 1960.
- Petersen, Forrest S., Rediess, Herman A., and Weil, Joseph: Lateral-Directional Control Characteristics of the X-15 Airplane. NASA TM X-726, 1962.
- <sup>4</sup>. Walker, Joseph A., and Weil, Joseph: The X-15 Program. Presented at AIAA 2nd Manned Space Flight Meeting, Dallas, Tex., Apr. 22-24, 1963.
- Taylor, Lawrence W., Jr., and Merrick, George B.: X-15 Airplane Stability Augmentation System. NASA TN D-1157, 1962.
- Boskovich, Boris, Cole, George H., and Mellen, David L.: Advanced Flight Vehicle Self-Adaptive Flight Control System. WADD Tech.

Rep. 60-651, Part I (Contract No. AF 33(616)-6610, Project No. 8226, Task No. 10889), Wright Air Dev. Div., U.S. Air Force, Sept. 30, 1960.

- 7. Tremant, Robert A.: Operational Experiences and Characteristics of the X-15 Flight Control System. NASA TN D-1402, 1962.
- 8. Sjoberg, S. A.: A Flight Investigation of the Handling Characteristics of a Fighter Airplane Controlled Through Automatic-Pilot Control Systems. NACA RM L55F01b, 1955.
- Cooper, George E.: Understanding and Interpreting Pilot Opinion. Aero. Eng. Rev., vol. 16, no. 3, Mar. 1957, pp. 47-51, 56.
- White, Robert M., Robinson, Glenn H., and Matranga, Gene J.: Résumé of Handling Qualities of the X-15 Airplane. NASA TM X-715, 1962.
- 11. Stillwell, Wendell H., and Drake, Hubert M.: Simulator Studies of Jet Reaction Controls for Use at High Altitude. NACA RM H58G18a, 1958.
- Cooper, N. R.: X-15 Flight Simulation Program. Paper no. 61-194-1888, Amer. Rocket Soc. and Inst. Aero. Sci., June 1961.
- Holleman, Euclid C., and Wilson, Warren S.: Flight-Simulator Requirements for High-Performance Aircraft Based on X-15 Experience. Paper no. 63-AHGT-81, Amer. Soc. Mech. Eng., Jan. 1963.
- 14. Hoey, Robert G., and Day, Richard E.: Mission Planning and Operational Procedures for the X-15 Airplane. NASA TN D-1159, 1962.
- 15. Hopkins, Edward J., Fetterman, David E., Jr., and Saltzman, Edwin J.: Comparison of Full-Scale Lift and Drag Characteristics of the X-15 Airplane With Wind-Tunnel Results and Theory. NASA TM X-713, 1962.
- 16. Matranga, Gene J.: Analysis of X-15 Landing Approach and Flare Characteristics Determined From the First 30 Flights. NASA TN D-1057, 1961.
- Weil, Joseph, and Matranga, Gene J.: Review of Techniques Applicable to the Recovery of Lifting Hypervelocity Vehicles. NASA TM X-334, 1960.
- Armstrong, Neil A., and Holleman, Euclid C.: A Review of In-Flight Simulation Pertinent to Piloted Space Vehicles. AGARD Rep. 403, 1962.
- 19. Matranga, Gene J., Dana, William H., and Armstrong, Neil A.: Flight-Simulated Off-the-Pad Escape and Landing Maneuvers for a Vertically Launched Hypersonic Glider. NASA TM X-637, 1962.
- Banner, Richard D., Kuhl, Albert E., and Quinn, Robert D.: Preliminary Results of Aerodynamic Heating Studies on the X-15 Airplane. NASA TM X-638, 1962.
- Kordes, Eldon E., Reed, Robert D., and Dawdy, Alpha L.: Structural Heating Experiences on the X-15 Airplane. NASA TM X-711, 1962.

 $|\xi| = |\xi| = |\xi| = |\xi|$ 

- 22. Watts, Joe D., and Banas, Ronald P.: X-15 Structural Temperature Measurements and Calculations for Flights to Maximum Mach Numbers of Approximately 4, 5, and 6. NASA TM X-883, 1963.
- 23. Videan, Edward N., Banner, Richard D., and Smith, John P.: The Application of Analog and Digital Computer Techniques in the X-15 Flight Research Program. Paper presented at International Symposium on Analog and Digital Techniques Applied to Aeronautics, Liege, Belgium, Sept. 9-12, 1963.
- 24. Walker, Harold J., and Wolowicz, Chester H.: Theoretical Stability Derivatives for the X-15 Research Airplane at Supersonic and Hypersonic Speeds Including a Comparison With Wind-Tunnel Results. NASA TM X-287, 1960.
- Row, Perry V., and Fischel, Jack: X-15 Flight-Test Experience. Astronautics and Aerospace Eng., vol. 1, no. 5, June 1963, pp. 25-32.
- McKay, James M., and Kordes, Eldon E.: Lending Loads and Dynamics of the X-15 Airplane. NASA IM X-639, 1962.

# COMPARISON OF X-15 AND ORBITAL LIFTING ENTRY TIME $L/D \approx 1$ TO 2



# COMPARISON OF X-15 AND LIFTING ENTRY VELOCITY

HOLMEMAN-10

MH-96 ADAPTIVE CONCEPT





Figure 3



EFFECT OF DAMPER GAIN ON ENTRY CONTROL ENTRY FROM 360,000 FEET RATE-COMMAND CONTROLS



----



Figure 7

# X-15 TERMINAL-GUIDANCE EXPERIENCE



Figure 9

HOLLEMAN

X-15 ENTRY RANGING



# RUNWAY REQUIREMENTS FOR LOW L/D LANDINGS



COMPARISON OF CALCULATED AND MEASURED TEMPERATURES



Figure 11