The extensive requirements for simulation in the design of the X-15 Research Vehicle became apparent very early in the development program. In early 1956, only weeks after NAA had been awarded the X-15 contract, a simple analog mechanization was being utilized, together with a crude three-axis controller to define the requirements for a manual reaction control system, a problem area which at that time was as new as space rendezvous is today. However, our most exaggerated estimates at that time regarding the application of simulation techniques in the development and flight testing of the X-15 are seen now in retrospect to have been most conservative. It may be said that the X-15 simulation requirements literally “grew” with the program. The flight simulation has been used in all design and testing phases; first to support the configuration and subsystem design; next to test and evaluate subsystems, displays, and control hardware, both in prototype and in final production form; and finally to provide flight test support and pilot training. This paper will review briefly the overall simulation program conducted during the 5-year development of the X-15 and will describe in detail the unrestricted six-degree-of-freedom mechanization which has been utilized during the past 3 years of the program. It will describe the most important of the many applications in which the simulator has been, and in fact is still being, utilized in the design, development, and flight testing of the X-15. Finally, it will be interesting to compare the simulation requirements of the X-15 with those of more advanced space vehicles and attempt to interpret problems or deficiencies encountered in the X-15 simulation as they may affect more advanced space mission simulation.

A review of the X-15 vehicle and its intended mission give an insight into the simulation requirements associated with the program. Figure 1 shows the X-15 vehicle and the control system configuration. The X-15 has an upper and lower movable vertical stabilizer for yaw control, and differentially operated horizontal surfaces for pitch and roll control while in the atmosphere. The reaction system for attitude control outside the atmosphere consists of small hydrogen peroxide rocket motors in the nose and wingtips. Electronic stability augmentation in the X-15 consists of rate damping about all three axes.

Figure 2 reviews the design mission and performance capability of the X-15. It is capable of attaining speeds in excess of 6000 feet per second, or Mach 6.0, and altitudes to 500,000 feet. Very early in the X-15 development it became apparent that a six-degree-of-freedom simulation, covering as much of the complete flight regime as possible, was necessary in order to explore the problems of manually controlled boost, re-entry, and space flight. In past airplane designs, stability and control problems could be adequately analyzed and solved by utilization of a five-degree-of-freedom (constant-velocity) simulation at a large number of given flight conditions. The addition of the sixth degree of freedom, namely the variation in velocity and altitude, entailed much increased complexity in the mechanization required and was not warranted, since the effects of these variations were not significant in the overall stability analysis. However, the X-15 can transverse its flight profile at a rate much greater than any encountered before. The rates of change of velocity and altitude, and correspondingly of dynamic pressure, during the boost and re-entry phase of the X-15 mission become large enough to greatly influence stability and control characteristics. The performance range of the X-15 makes the number of flight conditions which would be required to be investigated on a five-degree-of-freedom simulation prohibitively large. Also, it was necessary to allow the pilot to evaluate all the various phases of the mission during continuous simulated missions to establish proper compatibility with the human of the control systems, instruments, etc., during design. Thus, the requirements for at least a limited six-degree-of-freedom simulation was obvious purely from a stability, control, and human engineering standpoint, without regard for the many added advantages it would provide in pilot training, mission evaluation, and flight planning.

Because of the need for adequate aerodynamic data and early limitations of analog equipment, it was not expedient to initiate a six-degree-of-freedom simulation immediately. Consequently, during the first year of the program, efforts were directed toward specialized problems which could be solved on simpler simulations. Figure 3 presents a time schedule of the various simulation activities from the
initiation of the X-15 program to the present time. It is of interest to note the increasing sophistication of these studies. It is also interesting to note that the problems of early interest were those about which we knew the least, namely the exit and re-entry problem and the problems associated with reaction control. As mentioned previously, the simple reaction control mechanization was initiated in early 1956 and provided preliminary criteria for the reaction control system design. This was followed by a three-degree-of-freedom longitudinal mode mechanization of the exit and re-entry flight characteristics, utilizing very early aerodynamic data, for preliminary evaluation of control characteristics during these phases of the mission. The program showed that, in the longitudinal mode at least, manual control without augmentation was possible, but that augmentation was desirable. Next a “programmed q” analog mechanism was utilized to evaluate the compatibility of reaction and aerodynamic controls during the transition phases of exit and re-entry. Reaction control duty cycle requirements were also finalized. This simulation programmed the dynamic pressure variations of a design altitude mission and utilized constant aerodynamic data estimated at Mach 6. During the early simulation studies, the ability to include the pilot in the loop was provided by means of a simple cockpit simulator which included a reaction control stick.

The first six-degree-of-freedom mechanization which was utilized in the X-15 program was limited to Mach numbers greater than 2 and altitudes greater than 50,000 feet in order to simplify the mechanization. In this manner we were able to eliminate the complex variations in aerodynamic characteristics in the transonic regions and to minimize the range of variations of air density which had to be simulated. This simulation was utilized for approximately 8 months during 1957. During this period, the major design and development of the primary control system and the stability augmentation system on the X-15 was accomplished. Also, additional stability requirements were determined, and several design changes were incorporated in the basic configuration. The five-degree-of-freedom analog program shown on the schedule was run simultaneously with the early six-degree studies in order to evaluate stability and control characteristics, including roll coupling, at subsonic and transonic conditions.

One other simulation program which was accomplished during this period is worthy of note before we discuss the complete six-degree-of-freedom simulation. Since there was some concern as to the pilot's ability to control the X-15 under the dynamic loading conditions characteristic of exit and re-entry, a simulation program was conducted in the Human Centrifuge at the U.S. Naval Air Development Center, Johnsville, Pennsylvania, during the summer of 1958. In this program, the centrifuge was driven by computed signals from a limited six-degree-of-freedom analog simulation of the X-15 which was very similar to the one just described. Figure 4 shows, schematically, the method in which the analog computer was used to drive the centrifuge with a pilot operating as a closed-loop controlling function. The centrifuge was driven to follow the computed values of accelerations resulting from pilot inputs and airplane stability and response characteristics, so that the pilot was subjected to the actual G-loads of a specific mission or maneuver. During the centrifuge program, a total of 287 dynamic flights, consisting of the boost and/or the re-entry phase, were accomplished by the seven participating pilots. The results of this program showed that the pilot could control the X-15 during its most severe re-entry conditions, and further showed that, for the X-15 missions, static simulator results were not significantly different from those obtained under dynamic conditions. Consequently, no additional dynamic simulation effort has been necessary in the X-15 program.

Although the limited six-degree-of-freedom simulation provided invaluable information in early design of the airplane, it was soon apparent that it was inadequate. Because of limitations imposed on Mach number and altitude, problems associated with launch and roundout, space positioning, subsonic and transonic stability, and landing could not be investigated. By this time the potential value of the simulator in flight test mission planning and pilot training was apparent, and in these applications, complete simulation capability over the X-15 flight regime would be required. Therefore, the unlimited six-degree-of-freedom simulation was developed and has been in operation continuously since March of 1958. This simulation is capable of piloted or nonpiloted analysis throughout the X-15 flight regime, including launch maneuvers, boost and exit phase, reaction controlled ballistic flight, re-entry, and glide to landing flareout. The performance capability of the simulation covers the Mach range from 0.2 to 10.0 altitude to 500,000 feet, and angles of attack to 35 degrees. Simulated flights may be accomplished with speed brakes open or closed, with flap and landing gear extension effects, ventral jettisoning characteristics, and other
nonlinear effects. Missions may be flown using either the XLR-11 or the XLR-99 engine, including the effects of engine throttling and of thrust misalignment. Missions may be accomplished from the design B-52 carrier aircraft or from other advanced carriers such as the B-70. The dynamic effects of nonlinear changes in mass and moments of inertia during engine burning are simulated. Premature burnout of either engine may be simulated at any time, and propellant jettisoning may be accomplished at the required rates.

This simulation capability permits evaluation of all important contributions to the complete mission, with the exception of temperature. A simplified computation of skin temperature at critical points on the vehicle was mechanized on the analog computer and incorporated in the real-time problem solution early in the program. Temperature at one of several points on the vehicle was displayed to the pilot as an aid in remaining within limits during re-entry. However, it was found that this information merely told the pilot that he had exceeded limits and did not provide sufficient lead time to allow corrections once it was established that an over-temperature condition was imminent. Due to the limited application for which the temperature mechanization was suitable, and the equipment required, this part of the simulation was discontinued.

The capability of permitting piloted flights of the X-15 with this simulation is obtained by integration of the mechanization into the X-15 flight control simulator. This simulator is shown in figure 5. It consists of an exact duplication of the airplane cockpit, instruments, and control system. The complete operational flight control system provides exact system characteristics under operating conditions. Actual production components, including cables, push rods, bell cranks, the hydraulic system, artificial feel, etc., are utilized in exactly the same manner as the actual airplane. The electronics of the X-15 stability augmentation system are also included. The control system is duplicated in this detail in order to include all nonlinearities in closed-loop systems evaluation, and to provide the pilot with the exact feel characteristics of the airplane. All control displacements are available to the analog computer by means of electrical pickoffs on each aerodynamic control surface. The cockpit area, shown in figure 6, is a realistic simulation of the airplane configuration. The simulator has the same provisions for aerodynamic control as in the airplane, utilizing either the center stick or the right-hand console stick and rudder pedals. Reaction control is provided with the left-hand three-axis controller. The pilot has normal control over the stability augmentation system by means of the same controller panel as is installed in the air vehicle. The flight instruments, which are simulated in complete operational form, are driven by voltages from the analog computer. They include the inertial attitude indicator which provides pitch, roll, and heading; the inertial velocity, altitude, and rate-of-climb instruments; angles of attack and sideslip; roll rate; normal load factor; indicated air-speed; and for simulator test purposes only, an indication of dynamic pressure.

The equations utilized to simulate the X-15 in the unlimited six degrees of freedom are presented in figure 7. These are basically the classical equations of motion of the aircraft with respect to an Eulerian frame of reference. The equations and all aerodynamic parameters are mechanized in a body-axis system of coordinates. Orientation of the gravity vector and the geographical distance and position are obtained by means of conventional Eulerian angles. Due to the limited ground distance traveled by the X-15 in its design mission, a flat earth may be assumed as a reference. However, the centrifugal acceleration effect is included as a function of the X-15 horizontal velocity component and added directly to the normal gravity vector which is mechanized as a function of altitude. The terms and the equations which are considered variable include thrust, mass, velocity, gravity, inertia, and all aerodynamic coefficients which may not be assumed constant within the accuracy desired.

The analog computer complex used in the X-15 simulation is shown in figure 8. The linear equipment consists of five Model 16-31 Electronic Associates analog computers, incorporating 330 operational amplifiers. Additional nonlinear equipment required in the mechanization includes approximately 80 diode function generators, 25 computing servos, and three electronic multipliers; part of this equipment is shown in figure 9. The nonlinear variations of stability derivatives with Mach numbers and angles of attack are accomplished on four special interpolating servos which provide 17 interpolating points selected, as necessary, over the Mach range for each of the derivatives. The nonlinear variation of the derivatives with the angle of attack at the required Mach number points are obtained from a rack of 60 fixed-base diode function generators.

The greatest utilization of the simulator is obtained when the pilot is included as part of the control loop. Before discussing specific applications of the simulator in the X-15 program it might be well to review a complete simulated
flight of the X-15. Typical analog traces of a piloted design altitude mission as flown on the simulator are shown in figure 10. The flight begins at drop conditions, at Mach 0.8, at approximately 45,000 feet. The throttle is opened immediately after drop, and the pilot makes a pullup to $\alpha = 8$ degrees, which is maintained until the proper climb angle is established. (For a 250,000-foot-altitude mission, this angle is 30 degrees.) Pitch angle is then held constant until burnout, at which time an $\alpha = 0$ ballistic trajectory is established. It is well to note that this represents only one of several acceptable techniques for performing the exit phase. During the period of engine burning, control is required to correct for thrust misalignment. Burnout occurs approximately 90 seconds from drop, at a velocity of 6200 feet per second, at 160,000 feet. The effects of thrust misalignment are seen in the oscillations in angle of attack and sideslip. At burnout, the pilot begins use of the reaction control and continues this means of control throughout the ballistic phase of the trajectory. The recovery used in this particular flight was an angle of attack of 15 degrees, established at approximately 200,000 feet during re-entry. The required aerodynamic trim for this attitude can be set at any time, and the reaction control system then used to establish the required angle of attack. As the dynamic pressure builds up, the load factor is seen to increase, and for this mission, the pilot performed the recovery with the maximum of 5 G. Following the successful recovery, which occurs in this case at approximately 85,000 feet at approximately Mach 5, the altitude is held constant as the airplane decelerates until the desired descent speed is reached.

Consider now what this complete flight simulation allows in the way of system development and testing. Since the pilot can essentially fly the complete mission, a complete evaluation of controls, displays, and augmentation devices is possible long before flight. In the case of the X-15, the complete flight control system, including the stability augmentation system, was operating in the simulator a year before the first flight. The stability augmentation system, which was originally designed and specified on the limited 6-degree simulation was later included in a closed-loop simulation in its exact prototype form on the complete mechanization. These simulation tests on the complete system revealed several inadequacies due to the non-linear characteristic of the control system; these were corrected before flight. Other changes which were made in the X-15 as a result of simulator testing included control system feel modifications, display changes, and a redesign of the right-hand console grip.

The versatility of the combined simulator and analog mechanization has been more recently demonstrated by the design evaluation and hardware testing of two separate autopilot systems on the simulator. These were both complex adaptive-type autopilots which included attitude-hold modes, reaction and aerodynamic control integration, and other refinements to the basic X-15 control system. These autopilots were included as a part of the closed-loop control system, and their performance was completely evaluated under conditions of the X-15 mission profile. Considerable design changes and improvements were made as a result of these tests, and at the present time, one of these advanced systems is being readied for X-15 flight evaluation. During flight testing of this system, a simulator support program will provide the pilots with preflight training and familiarization with its operational characteristics.

In addition to systems development and stability analysis applications, the simulator has proved invaluable in studies involving the pilot, his control requirements and training, and in flight test planning and support. An example of these is the early development of reaction control techniques. Since the basic X-15 originally had no provisions for stability augmentation through the reaction control system, the control characteristics were those of a perfectly neutral, undamped system unlike any vehicle with which pilots were familiar. Prior to establishment of final reaction control fuel requirements, several pilots were trained on the simulator to perform this type control, and a realistic duty cycle was then obtained. It is significant that gross reductions in fuel requirements were obtained after a pilot had experience on the simulator. Also, it was found that only a minimum amount of experience was required (10 to 20 "flights") for the pilot to reach his near-optimum degree of efficiency.

More recently, the simulator has been utilized by the Air Force, NASA, and North American almost exclusively for pilot training and flight planning. In order to fully appreciate the value of a simulator in this capacity, it is necessary to consider in some detail the X-15 flight test program. First, of course, the cost of an X-15 flight is quite high, requiring that all possible benefit be derived from each mission in terms of research data. The cost factor is also reflected in the necessity for taking reasonably large steps in performance during the flight builds, which requires that each
flight be thoroughly evaluated prior to its acceptance. The safety aspect of research flight planning provides the greatest single requirement for adequate simulation. The simulator allows the research pilot to thoroughly evaluate all aspects of a proposed flight, including all conceivable malfunctions or emergency situations.

The ground positioning, or navigational problem, is a critical consideration in flight planning due to the limited glide range of the X-15. This problem is analyzed on the simulator, with the aid of a detailed map of the flight area (figure 11) on an X-Y plotter upon which the simulated flight path is plotted. This permits the pilot to actually fly simulated emergencies, such as premature engine shutdown, at all points along the proposed flight path, and determine the optimum approaches to the selected emergency landing sites. It is interesting to note that the plotting board used in the simulation is identical to the ones used at the ground station during an actual flight, except of course that, at the actual control station, the flight path is plotted from radar tracking signals rather than from analog signals. This permits the flight test engineer to review, or rehearse, the proposed flight with the pilot on the simulator.

As a result of 3 years of continuous operation of the X-15 simulator in many various applications, certain general conclusions may be made regarding operation, accuracy, and efficiency of complex analog simulations. The six-degree-of-freedom analog simulation has been operated in excess of 10,000 hours in support of the X-15. Over 5000 hours have been logged in the flight control simulator. The simulator is generally on a two-shifts-per-day schedule, and on this basis, an operational utilization of approximately 85 percent is realized. Down time may be attributed equally to equipment problems and to checkout. It has been found that, for a computer complex as large as this, daily problem checks are a requirement. So-called “dynamic” checks, or stability checks, are made by comparing the simulator with IBM-computed transients obtained during pre-programmed roll maneuvers at several constant-velocity flight conditions. These five-degree-of-freedom checks have been found to be most adequate in ensuring correct stability characteristics throughout the flight regime. Very good accuracy is obtainable with the analog computer in stability computations, since they generally involve short time transients for which the analog is well suited.

Performance checks are also made at regular intervals, and involve comparison of IBM-computed trajectories with analog results. It is in this area that the checks become most critical. Very minor discrepancies in the computer operation can cause excessive errors in performance checks, primarily in altitude and range. This is because of the long time computations involved (from 5 to 20 minutes, depending on the condition) and the resulting susceptibility of the solution to computer drifts and noise, and to nonlinear servo characteristics. It has been possible, however, to recognize the source of these errors and, by proper computer checks, to obtain the accuracy necessary for the X-15 performance problem. The accuracy usually obtained in computing such parameters as range, altitude, and velocity over a 20-minute simulated flight is within 2 percent.

Final proof of the validity of the simulation is, of course, demonstrated in how well it compares with actual flight results. The pilots who have flown the X-15 consider the simulator to be a very close simulation of the actual airplane flight characteristics. In fact, the simulator has become an integral part of the pilot's flight preparation program as a result of the pilot's own acceptance of the accuracy and value of the simulator. Figure 12 shows a performance comparison of XLR-11 maximum-speed flight with the analog-predicted flight which was run prior to the flight. The discrepancies noted are, to a great extent, the result of atmospheric variations, i.e., nonstandard days and wind shears. Figure 13 shows the same comparison for the maximum-altitude flight with the XLR-11 engine. During all speed and altitude buildup flights, simulator-predicted performance has been matched to within .1 Mach and 3000 feet altitude. The stability characteristics of the X-15 have also been adequately predicted on the simulator, although it is in this area that minor discrepancies in wind tunnel data reflect the largest differences in simulator matches. The simulation is used, in this regard, to determine the variation in stability derivatives necessary to obtain exact flight data matches, and in this manner the validity of wind tunnel data is established.

Figure 14 shows a simulator comparison of the data obtained during the landing of the first X-15 glide flight. This demonstrates the validity of the simulation in duplicating the low-speed dynamics and performance of the airplane, but at the same time, it may be used to indicate an area in which the simulation was proven to be
deficient. The pitching oscillation experienced during the landing flareout, although duplicated almost perfectly on the simulator after the flight, was not predicted from simulator experience prior to flight. The problem resulted from a higher level of control sensitivity associated with the side-arm controller than was expected. This characteristic was not predicted on the simulator because of lack of critical cues, such as the visual horizon and the actual motion of the airplane, during the landing simulation.

It is of interest to compare the X-15 simulation requirements with those of currently projected manual space vehicles, and to consider some of the expected problem areas in view of X-15 experience. In the X-15 program, the major simulation requirements have been described as being related to control system development and testing, stability evaluation, pilot task studies, mission planning, and pilot training. These requirements result primarily from the fact that the vehicle utilizes the man for command and control, and that it is designed to fly at conditions far advanced over any encountered at the time of the vehicle design. The extension of this reasoning to manned space systems is obvious. The system development and testing requirements for these advanced vehicles will far exceed those of the X-15 because of the greater number of systems requiring integration and pilot evaluation and because of their increased sophistication and complexity. The importance of early simulator evaluation of subsystems critical to the space mission is demonstrated by the advanced system programs which have been accomplished, or are being planned, on the X-15 simulation. The stability and control characteristics of aerospace vehicles, particularly during re-entry, will require simulator analysis and pilot evaluation over a much greater range of flight conditions than for the X-15. The effects of the expanded flight envelope will also be reflected in increased simulation requirements in areas of human engineering, mission planning, and pilot training.

Even these very general considerations leave no doubt that simulation will play an even more important part in space vehicle development and testing than was required on the X-15. Consider next the problems which may be expected in providing this required simulation capability. The critical problem areas which have been encountered in the X-15 simulation have already been described as being related primarily to performance. These resulted from long time computation requirements in which computer drift and accuracy limitations become critical. It is apparent that these problems will become more serious in space missions simulation because of the larger mission time. The ranges of important variables which must be mechanized for a typical aerospace configuration will be, in many cases, greater than those required in the X-15 simulation and will create additional scale-factoring problems. Typical of these are velocity, Mach number, and altitude. In some instances, however, the X-15 requirements may be the more severe. For example, the range of dynamic pressure for which the X-15 is designed (0 to 2500 psf) is much greater than will be required in winged re-entry vehicles. The rates of change of dynamic pressure in the X-15 mission are even more significant. Figure 15 shows dynamic pressure rate of change during re-entry as a function of re-entry angle. It is seen that the steep re-entry angles required for the X-15 result in much more severe dynamic pressure changes than are experienced by orbital re-entry vehicles.

Space simulation requirements will allow particular phases of the complete mission to be mechanized individually in order to limit the range of variables and to minimize the computation time required. For instance, simulation of the boost, orbit, and re-entry phases of a complete orbital mission in a single mechanization becomes impractical by current analog techniques. However, if each phase is mechanized individually, with appropriate scale factoring, satisfactory results may be obtained for most applications. For example, the major portion of the orbital re-entry problem may be simulated at altitudes above 100,000 feet. Since the X-15 simulation adequately duplicates air density from sea level to 250,000 feet, the requirements for simulation of air density for an orbital re-entry problem are no more severe than for the X-15.

Some preliminary studies have been conducted utilizing conventional analog techniques to mechanize various aerospace missions. The vehicles simulated were an orbital re-entry system and a lunar return vehicle. The X-15 flight simulator was used to allow pilot participation in analysis of such problems as high-angle-of-attack stability during re-entry and flight path control during aerodynamic deceleration from lunar return velocities. Analog data showing a piloted lunar return maneuver are shown in figure 16. As the vehicle approaches the earth at approximately 36,000 feet per second along an optimum flight path which has been established many hours earlier, the pilot rolls 180 degrees and, by utilizing aerodynamic lift, maintains a constant altitude as the velocity slows to sub-orbital. In this application, the analog simulation
was found to be quite adequate in establishing pilot capability and control techniques, since the critical portion of the problem (namely, the establishment of the proper approach trajectory) was assumed to have already been accomplished. Also, the maneuver considered required relatively high aerodynamic forces at velocities appreciably greater than orbital, so that the differences between gravity and aerodynamic effects were not critical. Figure 17 shows the effects of a 0.1 percent error in either of the components of acceleration during a simulated re-entry from a near-circular orbit in which aerodynamic drag is used to decelerate the vehicle at perigee. Here the effects on performance during re-entry are seen to be quite severe due to the near-equal values of gravity and centrifugal acceleration. It was apparent from these studies that the analog mechanization provided adequate simulation of both dynamic characteristics and performance, provided the computation time was minimized and good performance was not required at very-near-orbital velocities.

To summarize, it would be well to reiterate that the X-15 flight simulator, as it exists today, is the result of design requirements as projected early in the program. The requirement to include the pilot in the loop as an integral part of the systems development and testing provided the major justification for the detailed duplication of displays and flight controls, and for the extensive six-degree-of-freedom analog simulation of the airplane motion. Since the application for which the simulator has been utilized in the latter phases of the program (namely, mission planning and pilot training) were not clear cut in the beginning, we were fortunate that early requirements dictated the simulation approach which was pursued. It has been indicated that the X-15 simulation requirements were similar in many respects to those which may be expected in simulation of more advanced vehicles, and that the problems which were encountered are definite indication of the difficulties which may be expected. Consequently, it appears that the X-15 simulation requirements, techniques, and problems should prove helpful in future programs, both in early definition of the overall simulation program to be followed and in determining the best approach to accomplish the program.

Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>Cm</td>
<td>Pitching moment (nondimensional coefficient)</td>
</tr>
<tr>
<td>Cn</td>
<td>Yawing moment (nondimensional coefficient)</td>
</tr>
<tr>
<td>Cn</td>
<td>Normal force (nondimensional coefficient)</td>
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<tr>
<td>Cy</td>
<td>Side force (nondimensional coefficient)</td>
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<td>G</td>
<td>Acceleration of gravity (ft/sec²)</td>
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<tr>
<td>h</td>
<td>Altitude (ft)</td>
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<tr>
<td>Ixx</td>
<td>Moment of inertia about X-body axis (slug-ft²)</td>
</tr>
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<td>Iyy</td>
<td>Moment of inertia about Y-body axis (slug-ft²)</td>
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<td>Yaw rate</td>
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<td>S</td>
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<td>Vo</td>
<td>Velocity of the center of gravity (ft/sec)</td>
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<tr>
<td>Vx</td>
<td>Velocity component along X-body axis (ft/sec)</td>
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<tr>
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<td>Velocity component along Y-body axis (ft/sec)</td>
</tr>
<tr>
<td>Vz</td>
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<tr>
<td>α</td>
<td>Angle of attack</td>
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<tr>
<td>β</td>
<td>Angle of sideslip</td>
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<tr>
<td>Δ</td>
<td>Differential horizontal stabilizer deflection, roll control</td>
</tr>
<tr>
<td>δH</td>
<td>Horizontal stabilizer deflection, pitch control</td>
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<tr>
<td>δV</td>
<td>Vertical stabilizer deflection, yaw control</td>
</tr>
<tr>
<td>φ</td>
<td>Euler angle of axial rotation, roll</td>
</tr>
<tr>
<td>θ</td>
<td>Euler angle of elevation, pitch</td>
</tr>
<tr>
<td>ψ</td>
<td>Euler angle of azimuth, yaw</td>
</tr>
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REACTION CONTROL ACCELERATIONS

• PITCH & YAW - 2 1/2°/SEC²
• ROLL - 5°/SEC²

AERO CONTROLS
ALL MOVEABLE SURFACE
• HORIZONTALS - PITCH & ROLL
• VERTICALS - YAW

Figure 1. Flight Controls

TYPICAL MISSION
BALLISTIC TRAJECTORY
BURNOUT
T=88 SEC
ALT=158,000 FT
V=6340 FT/SEC

GLIDE BACK TO BASE

Figure 2. X-15 Research System
REACTION CONTROL MECHANIZATION
3° OF FREEDOM, LONGITUDINAL MODE
PROGRAMMED DYNAMIC PRESSURE
5° OF FREEDOM, CONSTANT VELOCITY
... ROLL COUPLING
LIMITED 6° OF FREEDOM
COMPLETE 6° OF FREEDOM
DYNAMIC CENTRIFUGE
... 6° OF FREEDOM

1ST FLIGHT

JFMAMJJASONO JFMAMJJASONO JFMAMJJASONO JFMAMJJASONO JFMAMJJASONO
1956 1957 1958 1959 1960

Figure 3. Flight Simulation Summary

ACCELERATION OUTPUTS
COORDINATE CONVERTER
CENTRIFUGE DRIVE SIGNALS

ACL COMPUTER FACILITIES

AMAL CENTRIFUGE
DISPLAY OUTPUT
ACCELERATIONS

CENTRIFUGE POWER

PILOT CONTROL MOTIONS

Figure 4. Dynamic Simulation
Figure 5. Flight Control Simulator

Figure 6. Simulator Cockpit

From the collection of the Computer History Museum (www.computerhistory.org)
\[ \dot{V}_x = \ddot{y} \sin \theta + \frac{T - \tau_0 \tau_0 c}{m} - V_y \beta + V_y \gamma \]
\[ \dot{V}_y = \ddot{y} \cos \theta \sin \phi + \frac{\tau_0 s}{m} \left( C_{v_x} \beta - 1.6 C_{v_z} \gamma - 1.5 C_{v_z} \gamma' - V_x \gamma + V_y \gamma \right) \]
\[ \dot{V}_y = \ddot{y} \cos \theta \cos \phi + \frac{\tau_0 s}{m} \left( C_{v_x} \beta - 1.6 C_{v_z} \gamma - 1.5 C_{v_z} \gamma' - V_x \gamma + V_y \gamma \right) - V_y \beta + V_x \gamma \]
\[ \dot{\psi} = \frac{q_0 s b}{l_{xx}} \left( C_{v_x} \beta + C_{v_z} \gamma + C_{v_z} \gamma' + \frac{b}{2 V} C_{v_x} \beta \right) + \frac{1}{l_{xx}} q \gamma \]
\[ \dot{\phi} = \frac{q_0 s b}{l_{yy}} \left( C_{v_x} \beta + C_{v_z} \gamma + C_{v_z} \gamma' + \frac{b}{2 V} C_{v_x} \beta \right) + \frac{1}{l_{yy}} q \beta \]
\[ \dot{v} = \frac{q_0 s b}{l_{zz}} \left( C_{v_x} \beta + C_{v_z} \gamma + C_{v_z} \gamma' + \frac{b}{2 V} C_{v_x} \beta \right) + \frac{1}{l_{zz}} q \right] \]
\[ \dot{\phi} = \ddot{y} \sin \theta + \ddot{y} \cos \theta \sin \phi \]
\[ \dot{\psi} = \ddot{y} \sin \theta + \ddot{y} \cos \theta \cos \phi \]
\[ \dot{\phi} = \frac{V_x}{V_0} \cos \beta \]
\[ \dot{\psi} = \frac{V_y}{V_0} \sin \phi \]
\[ \dot{x} = \left[ V_x \cos \theta \sin \phi + (V_y \sin \phi + V_y \cos \phi) \sin \theta \right] \cos \phi + \left[ V_y \sin \phi - V_y \cos \phi \right] \sin \phi \]
\[ \dot{y} = \left[ V_x \cos \theta \sin \phi + (V_y \sin \phi + V_y \cos \phi) \sin \theta \right] \cos \phi - \left[ V_y \sin \phi - V_y \cos \phi \right] \sin \phi \]
\[ \dot{z} = \dot{v} \sin \phi - V_y \cos \Theta \sin \phi - V_y \cos \Theta \cos \phi \]
\[ \dot{\phi} = 32.17 - \kappa_1 \kappa_2 \]

Figure 7. Six-degree-of-freedom Equations of Motion
Figure 8. Analog Simulation

Figure 9. Nonlinear Computing Equipment
Figure 10. Design Altitude Mission

Figure 11. Variplotter for Simulated High-range Plotting
Figure 12. X-15 Maximum-speed Flight

Figure 13. X-15 Maximum-altitude Flight
Figure 14. First Glide Flight Landing Flareout

Figure 15. Re-entry Dynamic Pressure Variation
Figure 16. Lunar Vehicle Re-entry

Figure 17. Effects on Analog Errors in Near-circular Orbit Computations