Systems approach to flight controls

Systems analysis coupling theory, simulator work, and flight testing defines the performance guiding electronic control development

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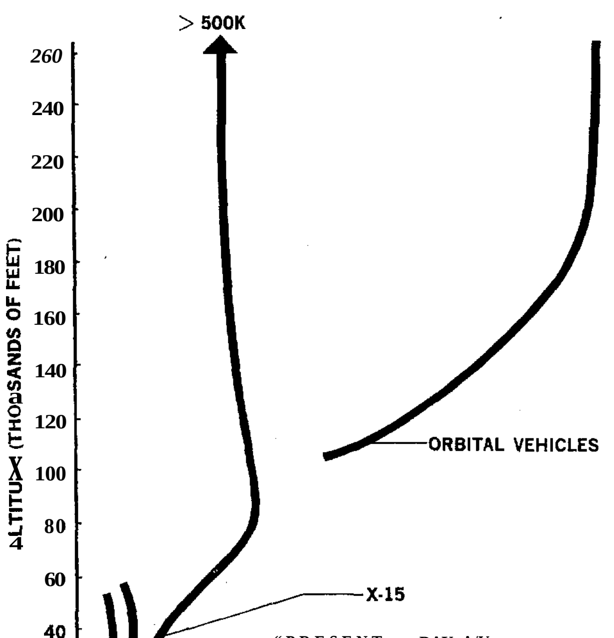
WE have seen successive generations of manned vehicles expand the flight envelope, as depicted here, bringing wave after wave of new characteristics and problem areas. The demands of high-performance flight necessarily toughened and unified the designer's approach to problems, and gave rise to a highly conscious attack on the ***system,*** eventually in the form of a mathematical model describing its properties with great exactness. Producing this model often became the major work of a development program.

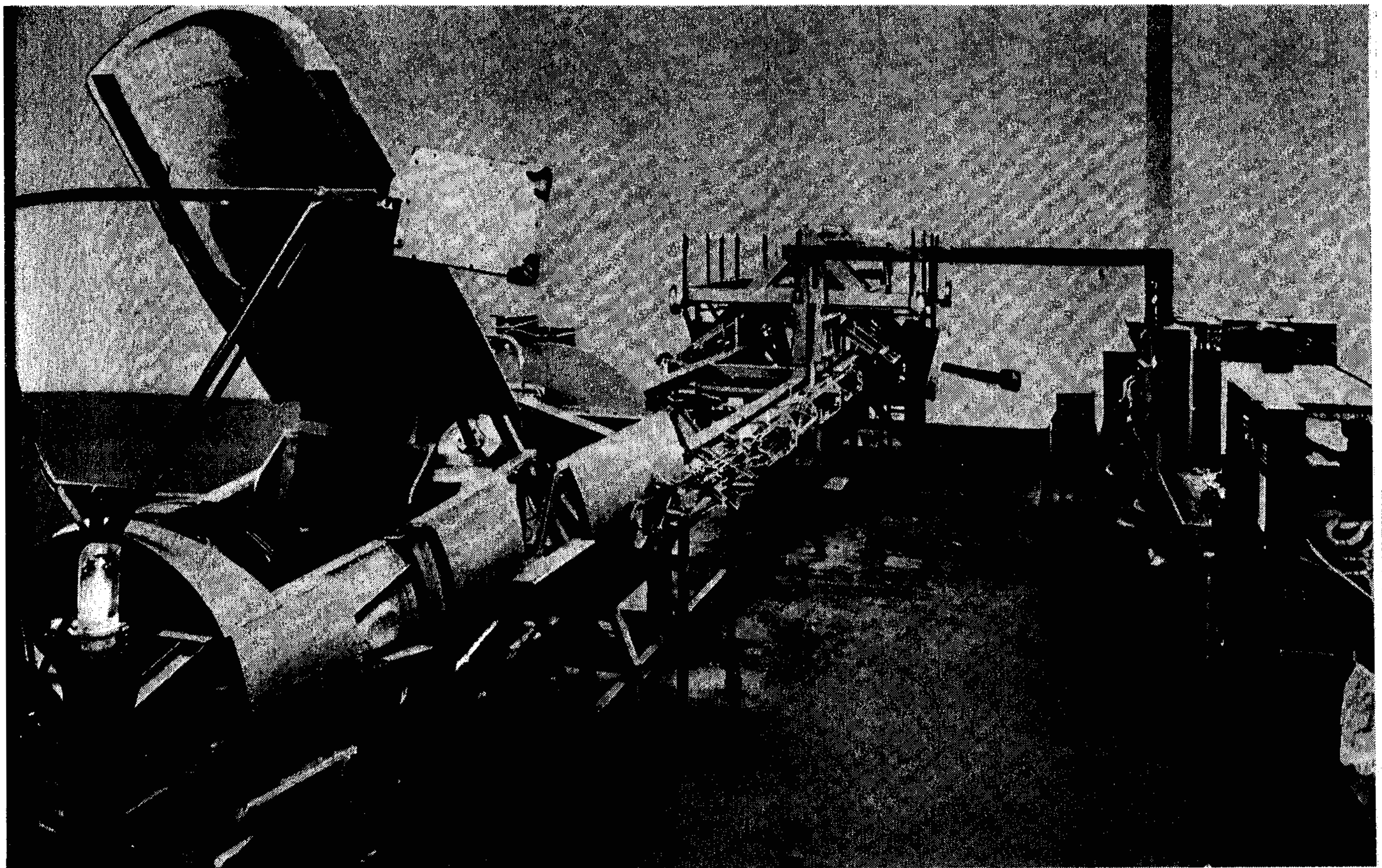
Recently, work on flight controls has led the development of the systems approach. Reasonable correlation between the pilot and an analytical representation has been obtained for specific conditions. This analytical representation has enabled the systems engineer to analyze handling qualities utilizing stability characteristics of automatic controls. With certain performance criteria available, control functions can .then be integrated into the basic system, the particular configuration of any given system being the result of a process of both analysis and synthesis. At this stage decisions can be made as to the type of controller required—open loop, closed loop, fixed gain, adaptive, etc.—and as to advantages and disadvantages of mechanical, electrical, and hydraulic hardware. Since flight-control systems included multiple control loops and high gains, the ease with which these can be accomplished electronically has become significant.

FLIGHT ENVELOPE EXPANSION



At the time **of X-15** basic **design,** there were two new areas in flight-control study: control outside the sensible atmosphere and dynamics of high-angle-of-attack flight at high velocities. For the first, an entirely separate control system had to be designed which made use of low-thrust reaction motors. For the second, problems attendant with large aerodynamic coupling effects, pilot capability under high acceleration stresses, and high-control sensitivities had to be explored. The integration of suitable flight controls into the **X-15** was then a task of using analytical methods of flight dynamics as well as such useful aids as analog computing equipment and flight-control simulators to formulate a system providing satisfactory control characteristics throughout the flight envelope.

The X-15 manual reaction control system was designed for operation as an attitude command and rate-damping space control with the pilot-display combination being used to close the control loop. It consisted of 12 hydrogen-peroxide reaction motors, grouped in pairs at strategic places on the vehicle. The pilot controls the thrust of these motors with a three-axis stick on the left side in the cockpit. The control stick mechanically links to the propellant metering valves, and stick motion in each of the



Operating characteristics of the four flight-control systems diagrammed below received realistic analysis in this simulator, which features complete solution for the X-15 flight envelope by means of analog computing equipment.

three independent axes produces an angular acceleration about the appropriate axis.

It was found on the X-15 that, although this manual system was completely satisfactory once a pilot familiarized himself with it, improved operation could be achieved by closing the loop through a rate-sensing gyro in each axis, thereby providing automatic rate damping. With such a system the pilot's workload decreased, and more precise attitude control was possible, with a resultant increased usefulness in the high-altitude research capabilities of the vehicle.

Automatic Rate Damping Limited

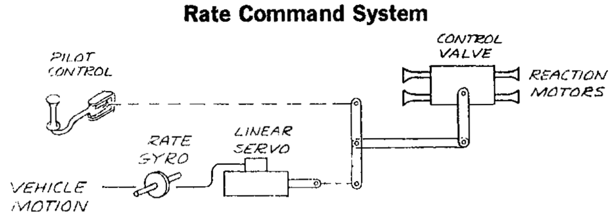
However, implementation of an automatic rate-damping system (designated **RAS** for Reaction Control Augmentation System) was restricted somewhat by the following constraints:

1. Operation of the basic manual Rate Command System (RCS) was not to be changed materially.

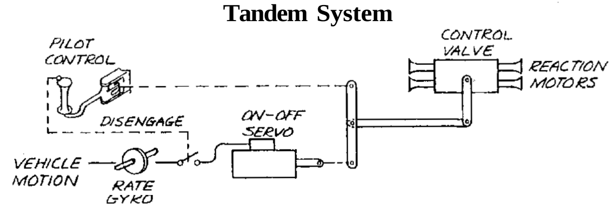
2. The hardware of the **RAS** should be easily integrated into the existing RCS.

3. Due to the fixed amount of propellant available for the reaction-control mode, that used by RAS should be a minimum. (CONTINUED ON PAGE 74)

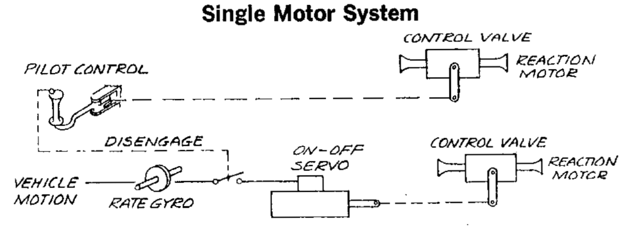
Rate Command System



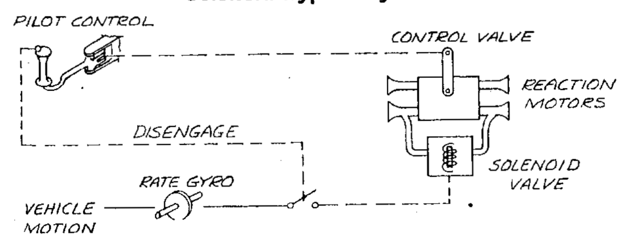
Tandem System



Single Motor System



Solenoid Bypass System



Flight Controls

(CONTINUED FROM PAGE 37)

With these constraints in mind, four possible designs were proposed for investigation.

The first was a limited RCS in which damping and pilot inputs to the reaction-motor control valves are mechanically summed on a walking beam, as indicated in the top diagram on page *37.* The rate-command function was limited due to the desirability of manual-override capability, which was accomplished by limiting the authority of the linear servo. In this system the pilot input is a linear function of the angular rate of the vehicle, within the limits of the servo. That this is so can be seen by noting that the mechanical displacement of the control valve is a function of the control-stick input, which is a constant for a given position, and the damping input, which is a constant for a given angular rate. When the two positions cancel, the valve shuts off and a constant rate is achieved. If either the stick position or the rate signal change, the valve is again opened until its position is again nulled. For pilot inputs greater than the servo authority, an angular acceleration is commanded as in the normal manual system.

A second system, labeled "Tandem" in the diagram on page **37,** also used a mechanical summation technique. The servo in this configuration is an on-off device and acts only in the absence of pilot inputs. The characteristics of the damping loop are set by the threshold and authority of the servo, which in turn are dictated by controllability and propellant-consumption considerations. The damping loop is disengaged during pilot command so that propellant is conserved by avoiding opposing thrusts of the damper trying to cancel pilot input.

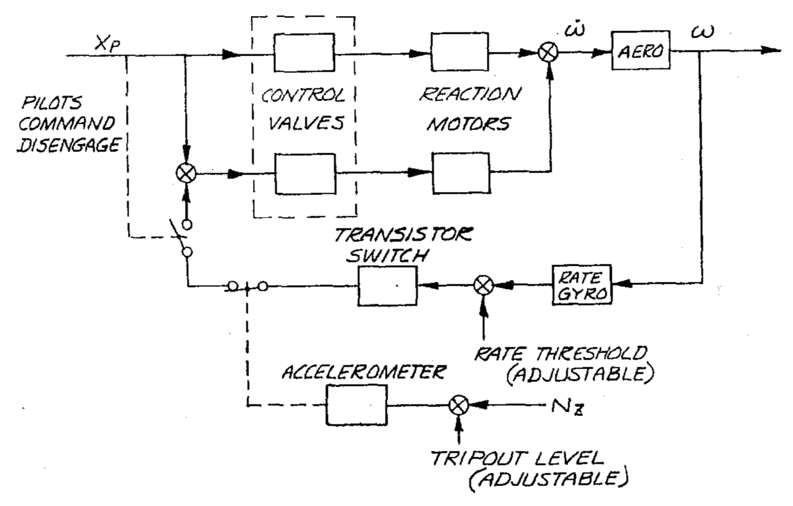
The duality of the manual system suggests a third design in which a "single motor system" is used for manual control and the other for damping, as indicated in the diagram on page *37.* This system is predicated on the fact that satisfactory pilot control can be achieved by single-system operation. This configuration also incorporates the damping-disengage feature for propellant conservation.

Finally, the solenoid bypass system diagrammed on page *37* has a separate on-off solenoid valve which bypasses the manual-control valve on one of the reaction motors. The damping inputs are then developed from an on-off condition of one of the dual motors. Damper disengagement by pilot command is also a feature of this configuration.

A flight-control simulator was used to evaluate the characteristics of these various designs. The simulator, shown on page *37,* featured complete, 6-deg-freedom analog-computed problem solution for the entire flight envelope of the X-15. Of particular interest in this evaluation were the high-altitude and re-entry portions of the envelope, which allowed evaluation of system operation during near-zero dynamic pressure and also during the atmospheric re-entry transition. Using analog computing equipment to represent the various proposed configurations, each was optimized as well as possible **and** these **four** optimum **systems** were tested for operating characteristics.

The solenoid bypass configuration proved the most satisfactory for rate damping augmentation in the **RCS.** The RCS, although providing desirable handling characteristics from the pilot-control standpoint, operated very similar to the on-off systems due to the presence of nonlinear elements in the form of the manual-control valve, Its slightly superior control characteristics did not justify the added system complexity of the RCS. Single motor system operation resulted in an undesirable limitation of pilot control during re-entry and was therefore unacceptable. The tandem was comparable to the solenoid bypass configuration in operation, the principal differences being the hardware involved. The implementation of the bypass system in which the existing mechanical system would be essentially unchanged was felt to offer the most satisfactory choice of the two. **A** block diagram of the final solenoid bypass system appears on this page. The automatic cutoff function is to disengage the system after sufficient effectiveness of the aerodynamic controls is present.

AUGMENTED REACTION CONTROL SYSTEM



Rate Damping Integrated

The design of an automatic rate-damping system for use with the manual reaction-control system yielded an over-all system which was readily integrated into the existing control system and provided increased capability of the air vehicle in the research field due to easier and more precise control by the pilot. The system exhibited superior operating characteristics in all regions of its intended use and satisfactorily fell within the constraints imposed upon its design.

The **X-15** high-altitude flights required some very high angles of exit from the sensible atmosphere and therefore very steep re-entry angles. The requirements determined by the integrity of the structure limit the amount of normal load factor, the maximum temperature, and the maximum dynamic impact pressure to which the vehicle can be safely subjected. These requirements then determine the flight profile which must be met to accomplish the flight successfully. The flight profile requires a program of angle of attack directly related to the normal load factor. For high-altitude missions, load factor on the air vehicle must be maintained at a relatively high value so that the vehicle will hot enter too deeply into the atmosphere during re-entry. The high load factor requires large angles of attack which, ,,on the **X-15,** led to a handling-qualities problem. Since the **X-15** must fly into these areas, it was necessary to define the problems, their causes, and provide for solutions under all conditions.

The first step in the definition of the problem was description of the vehicle. Experience has shown that for perturbation studies of handling qualities the longitudinal and lateral-directional modes of the vehicle can be studied separately and, in addition, velocity can be looked upon as a constant, such that a series of individual studies can be made at various velocities. The sum total of these studies defines the handling qualities. The equations of motion of aircraft dynamics are well defined; and to provide ease of analysis, linear simplified lateral-directional equations are used.

The following equations are deemed satisfactory for an example of the definition of the lateral-directional dynamics of the vehicle and enable these characteristics to be easily included in an analytical study of the vehicle.

$$\dot{p} = L_p p + L_\beta \beta + L_{\delta_a} \delta_a$$
$$\dot{r} = N_r r + N_\beta \beta$$
$$\dot{\beta} = -r + Y_\beta \beta + \alpha_T p$$

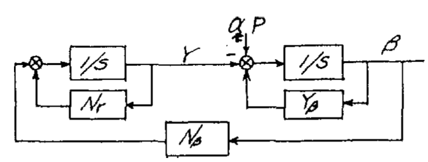
In LaPlace notation with the forcing function on the right:

$$L_\beta \beta + (L_p - S)p = -L_{\delta_a} \delta_a$$
$$N_\beta \beta + (N_r - S)r = 0$$
$$(Y_\beta - S)\beta + \alpha_T p - r = 0$$

SYMBOLS

δ_a	Aileron deflection
p	Roll rate
r	Yaw rate
β	Angle of side slip
ϕ	Rank angle
α_T	Trim angle of attack
N	Yaw angular acceleration
Y	Side acceleration/velocity
L	Roll acceleration

These equations represent two mutually perpendicular aircraft axes considered in the lateral-directional aerodynamics, the first being the lateral axis, or the roll about the center line, and the second being the directional mode, or its translation and rotation in a sideways manner. To investigate the interaction of one axis upon the other, one alone *is first* considered. The directional mode is made up of the last two equations, which can be put in the block-diagram form shown here.



The resultant dynamics of the directional mode are

$$S^2 - (Y_\beta + N_r)S + Y_\beta N_r + N_\beta$$

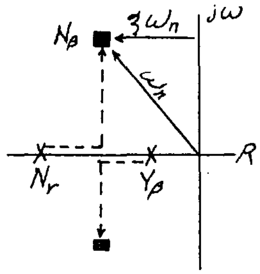
with the natural frequency defined as

$$\omega\eta = \sqrt{Y_\beta N_r + N_\beta},$$

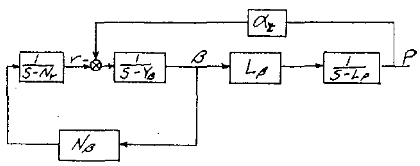
and damping ratio as follows:

$$\frac{Y_\beta + N_r}{\sqrt{Y_\beta N_r + N_\beta}}$$

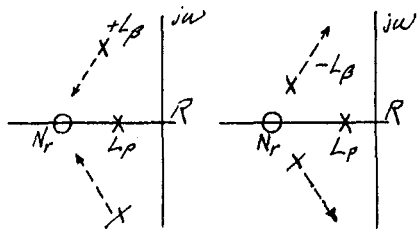
This is shown on a root locus plot here as a combination of the two lag terms of $1/N_r$ and $1/Y_\beta$ with the stiffness term of N_p giving rise to the two complex poles.



With the inclusion of roll coupling, these roots are modified according to the terms $\alpha_A p$ and L_β through the lag of the rolling time constant $1/L_p$. This is shown below in block-diagram form giving the complete lateral-directional dynamics.

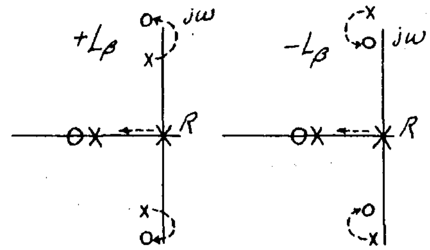


With $\alpha_T p$ being normally positive for positive load factor, the sign of roll-yaw coupling is determined by L_β, which is a strong function of angle of attack. The locus of roots with the roll coupling added show the decrease in static directional stability with a $+L_\beta$ and increase with $-L_\beta$, as follows:



To determine lateral-control capability, the transfer function for roll angle to aileron input from the aforementioned equations is obtained; and with this as the major part of the characteristic equation for the pilot-airframe combination and using a 0.5-sec lead for the pilot (which research determined as a reasonable approximation) we obtained the root loci of $\pm L_\beta$ with closed-loop operation as shown below.

$$\phi/S_a = \frac{L_{\delta a}\,[S^2 + (-N_r - Y_\beta)S + N_\beta]}{S[S^3 + (-Y_\beta - N_r - L_p)s^2 + (N_\beta - \alpha_T L_\beta + Y_\beta L_p + N_r L_p) - L_p N_\beta + L_\beta N_r \alpha_T - Y_\beta N_r L_p]}$$

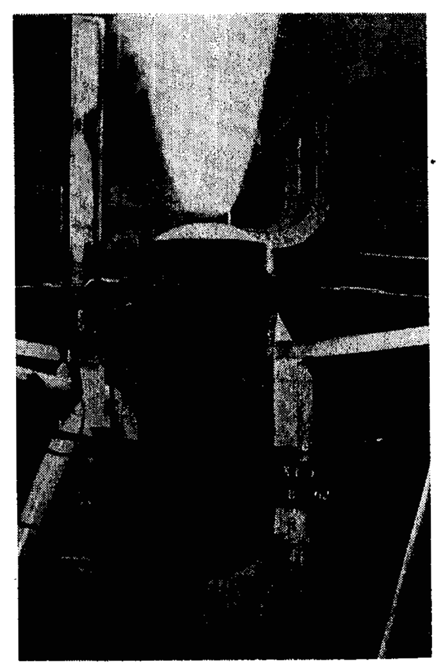


As indicated, $+L_\beta$ leads to a dynamically unstable control and $-L_\beta$ gives improved dynamic stability. The X-15 at high speed and high angle of attack has $+L_\beta$ and without augmentation the pilot-airframe combination is unstable. This instability was first demonstrated on the X-15 flight simulator and was subsequently verified in actual flight.

As previously seen, the handling-qualities problem stems from combination of poorly damped directional mode with adverse side-slip coupling of relatively large magnitude. The approach to the solution of the problem could be either improving the directional damping of the vehicle or minimizing the roll due to yaw. Improving the directional damping would effectively **be** increasing N_r. This can be done effectively with a yaw damper utilizing yaw rate as an input to the vertical. To minimize the roll due to yaw, a roll rate feedback can be used which effectively increases L_p. Therefore, for a given roll acceleration due to side slip, the resultant roll rate will be significantly reduced due to the operation of the roll augmentation which operates through the roll-control surface.

Through this system approach, it has been possible to make the task of integrating subsystems into an overall design easier and to produce an optimum configuration in a minimum time. ♦♦

Segmented Fiberglass-Case Solid Motor Fired by UTC



A 12,000-lb-thrust solid-propellant motor composed of three fiberglass-case segments joined by a flightweight mechanical joint fires at United Technology Corporation's Development Center near Morgan Hill, Calif. The company believes this to be the first firing of a segmented solid motor with such a case and a breakthrough in joint development for fiberglass cases.