equip the digital computer with a static store which has a capacity of about 1000 bits, into which data may be entered by means outside the computer (either manual or automatic) and which the computer reads in parallel just as an equivalent amount of electrostatic or magnetic core memory.

In addition to changes of equipment, there are a number of refinements which can be made in the present procedures for using these equipments and for programming both the analog and digital computers. Since the optimum choice of procedures is strongly influenced by the nature of the equipment employed, a discussion of procedural refinements is not felt to be worthwhile at this time.

In closing, it should be observed that the suggested improvements must be considered as being tentative until more experience is gained with the prototype and until the preferred means of implementing the facility can be more definitively specified.

ACKNOWLEDGMENT

The authors wish to acknowledge the assistance of Leonard Taback, J. Howard Wright, Jr., Emile S. Sherrard, David Friedman, and many others of the staff of the Data Processing Systems Division for their contributions to the design and fabrication of the prototype facility. They also wish to acknowledge the assistance and guidance of Lt. Richard L. Deininger of the Aero Medical Laboratory, WADC.

Discussion

W. McLean (North American Aviation): Please list reports or references describing hardware use (analog-to-digital conversion, etc.) and results obtained to date.

Dr. Skramstad: There have been no reports published as yet describing the hardware used. However, it will be described in a future report that will be submitted to the Wright Air Development Center.

S. Kwiatkowski (Avro Aircraft): In aircraft application, how many channels of analog-to-digital conversions and vice versa were required?

Dr. Skramstad: We have two channels for analog-to-digital and two channels for digital-to-analog conversion.

Mr. Kwiatkowski: How much time was spent in making the installation operational?

Dr. Skramstad: The equipment is now all built and most of the components are operating, but the installation is not yet operational. We are still in the debugging stage. We hope that it will be in operation very shortly.

Facilities and Instrumentation Required for Real-Time Simulation Involving System Hardware

A. J. THIBERVILLE†

THE design and testing of the aeroelastic flight control system for the B-58 has been accomplished with the aid of numerous studies conducted on the analog computers at Convair, Fort Worth, Texas. These studies have evolved from simple two-degree-of-freedom perturbation equations with simulated autopilots to the full-scale longitudinal and lateral total equations tied into the actual flight control system used in the airplane itself.

In this presentation, the problems involved in testing the flight control system in the longitudinal mode are considered. The analog computer was used to solve the airframe equations of motion and to simulate any needed elements of the autopilot and power control system for which actual hardware was not available.

The need for this study manifested itself in a threefold manner:

1) To completely test and wring out, under all conditions, the flight control system to be used in the airplane,
2) To ascertain the degree of control that a pilot would possess under adverse conditions, and
3) To familiarize the flight crews with the handling and instrumentation of the ship in preparation for actual flight.

The satisfaction of each of these three needs has been realized and is responsible in part for the success of the flight test program of the B-58.

The discussion will be begun by presenting a flow chart or block diagram of the different components considered in the study.

First, the purpose and operation of each block will be described in general, and then some details will be examined by discussion of the associated equipment and the listing of individual problems connected with each.

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A schematic drawing of the components and plan of intelligence used in the autopilot system test is shown in Fig. 1. Except for the air data computer, which was simulated by the analog equipment, the autopilot existed and operated as it would in actual flight. The central unit assembly, the heart of the system, correlated incoming commands, guidance, and reference signals and, by proper channeling to the power control system units, accomplished control of the airplane.

The power control linkage package responded to commands from the pilot and autopilot and effected corresponding motion of the control surfaces. In this instance, the control surfaces, which are called elevons in a delta wing airplane, act only as elevators.

The cockpit simulator, naturally enough, was used to house the pilot, his flight instruments, and controls.

Incidentally, the pilot was by no means excluded from this study. He was considered just as much a part of the complete system as any other piece of equipment listed and might as well have had a response study run on him which would have shown accuracy, resolution, and tolerance values equally as well as any of the studies seen on any of the predominating servos. He was the unit completing the closed loop system.

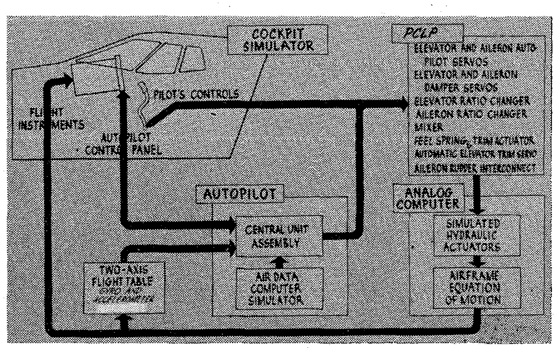

Fig. 1—Autopilot system's test.

The two-axis flight table, driven by Θ, the pitch angle of the airframe, supported the flight control system's gyro and accelerometer packet which then in turn fed the autopilot.

The analog computer consisted, with the exception of twenty-four channels of Reeves diode function generators, mainly of Electronic Associates' 16-31-R equipment.

The following equipment was used:

- 193 amplifiers
- 227 potentiometers
- 11 servos
- 10 electronic multipliers
- 6 resolvers
- 24 diode function generators
- 7 relays
- 4 recorders
- 16 diode limiters
- 2 plotting boards.

A study of the equations of motion of the airframe will serve as an aid in examining the details of these various components.

In Fig. 2, in addition to the auxiliary equations, the three main longitudinal equations are presented, namely, lift, drag, and pitching moment, from which the angle of attack, the velocity or Mach number, the pitch angle, and the altitude can be obtained. Because these are total equations containing the nonlinear coefficients which vary with flight conditions, *i.e.*, Mach number, altitude, angle of attack, etc., the representation of the airframe could be flown through the full range of speeds and altitudes for which it was designed.

$$\text{Lift: } \dot{\alpha} = \dot{\theta} - q\frac{s}{mV}\{C_L + C_T \sin(\alpha+\epsilon)\} + \frac{g}{V}\cos(\theta-\alpha)$$

$$\text{Drag: } \dot{u} = -q\frac{s}{m}\left\{C_{D_{\min}} + K_\delta \delta_e(\delta_e + 2\Delta\delta_e) + \frac{C_{D_L}}{C_L^2}\left[C_L - \Delta C_L + \frac{\partial \Delta C_L}{\partial \delta_e}\delta_e\right]^2 - C_T\cos(\alpha+\epsilon)\right\} - g\sin(\theta-\alpha)$$

$$\text{Pitch Moment: } \ddot{\theta} = q\frac{s\bar{c}}{I_{YY}}\left\{C_{m_0} + C_{m\alpha(\bar{c}/4)}(\alpha - \alpha_{L_0}) + C_{m\delta_e(\bar{c}/4)}\delta_e + \delta_{RS}C_{m\delta_{RS}(\bar{c}/4)} + C_L(CG - .25) + C_T\frac{d}{\bar{c}}\right.$$
$$\left. + \left[C_{m\dot{\alpha}(\bar{c}/4)} + \frac{\partial C_{m\dot{\alpha}}}{\partial CG}(CG - .25)\right]\frac{\bar{c}}{2V}\dot{\alpha} + \left[C_{mq(\bar{c}/4)} + \frac{\partial C_{mq}}{\partial CG}(CG - .25)\right]\frac{\bar{c}}{2V}\dot{\theta}\right]$$

Auxiliary Equations

$$\text{Lift Coefficient: } \sum C_L = C_{L\alpha}(\alpha - \alpha_{L_0}) + C_{L\delta_e}\delta_e + C_{L\delta_{RS}}\delta_{RS}$$

$$\text{Normal Acceleration: } n_a - 1 = q\frac{s}{w}[C_L + C_T\sin(\alpha+\epsilon)] - (X_a - CG)\frac{\bar{c}}{g}\ddot{\theta} - 1$$

$$\text{Hinge Moment: } HM_e = 2M_{AC}q[C_{H_0} + C_{H\alpha}\alpha + C_{H\delta_e}\delta_e]$$

$$\text{Thrust: } T = [T_{\text{MIL}_{SL}} - \Delta T_{\text{MIL}_h}][\text{M.F.}T_{\text{RPU}} + T_{\text{NPU}}]$$

$$\text{Indicated Velocity: } V_{\text{IND}} = V\left[1 + \frac{h}{300{,}000}\right]\sigma^{1/2}$$

$$q = 1/2\rho V^2 \qquad M = \frac{V}{a} \qquad T = qsC_T$$

Fig. 2—B-58 longitudinal total equations.

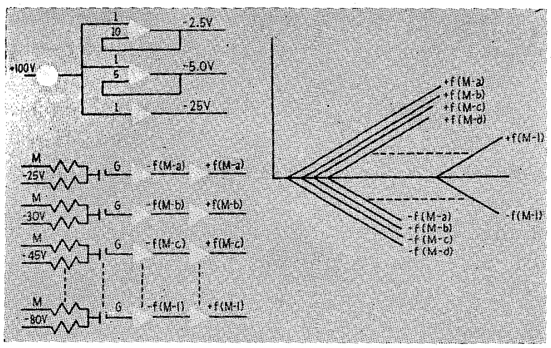

Fig. 3—Fixed break point method.

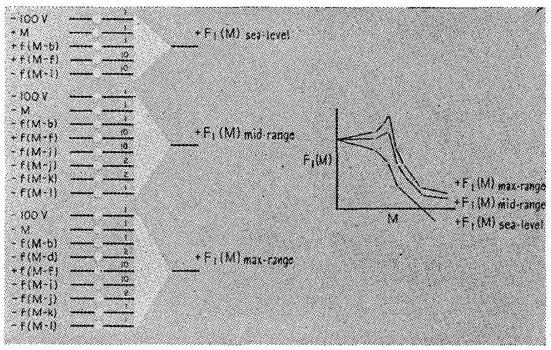

Fig. 4—$F_1(M)$.

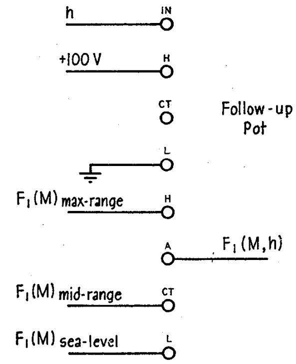

Fig. 5—$F_1(M,h)$.

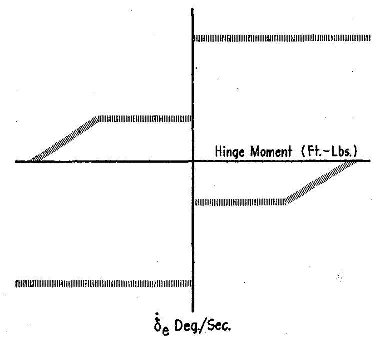

Fig. 6—Elevon rate limit.

To do so, it was necessary to generate some 31 nonlinear functions, eight of which were functions of two variables so that a total of 43 generators was needed. Because only 24 channels of diode function generators were accessible, 19 coefficients which were functions of Mach number were selected and simulated with what is known as the fixed break point method, as shown in Fig. 3.

This simulation was effected by selecting the group of functions which needed break points at a minimum number of points within the Mach range. By using resistors, diodes, and amplifiers, these individual break points, with both positive and negative constant slopes, were then generated on the computer patch board.

All of the break points, either positive or negative, needed to constitute the individual functions were then gathered together on amplifiers, as shown in Fig. 4, by using gain pots to adjust the slopes.

This method proved to be expensive in pots, amplifiers, and time but entirely adequate to fulfill the need since other means were not available.

To extend nonlinear coefficients to functions of both Mach number and altitude, the assumption was made that these coefficients were linear, in altitude, over two ranges; that is, from sea level to some midrange and then again from this midrange to the maximum ceiling. This approach led to three functions, one for each altitude, which varied with Mach number alone.

These functions were then placed respectively on the low, center tap, and high end of a multiplying pot of a servo, as shown in Fig. 5. The servo, driven by (h), the altitude, then produced the function $f\ (M,h)$ on the arm of the multiplying pot. By having three multiplying pots on each servo, all eight functions of two variables on three servos were accommodated.

An elevon rate limit was needed, which, as can be seen in Fig. 6, is somewhat of an awkward constraint to be imposed on the elevon rate since it is a function of the hinge moment as well as the direction of motion.

This limiting rate was accomplished by a circuit consisting mainly of diodes, pots, and high-gain amplifiers (Fig. 7). Its operation depended upon two general parts. One was a pair of electrically symmetrical function generators, which generated the elevon rate limit as a function of hinge moment. The other was a pair of symmetric absolute value summing amplifiers. The inputs to these summers were the rate limits, the elevon commands, and a feedback from the time lag. These signals caused the outputs to be the difference between the rate and rate limit when the limit was exceeded. This difference was then fed into the time lag out of phase with the rate and therefore subtracted from the rate the amount that the limit was exceeded.

As long as the rate was within its limits, the outputs remained at zero and thus allowed the δ_e command to be affected only by the time lag.

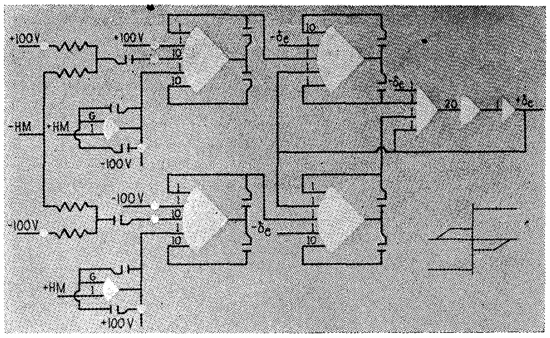

Fig. 7—Elevon rate limit circuit.

Ordinarily, diode limiters tend to "give" when hit by a large voltage. This circuit did not depend upon this type of limiting but rather upon the cancellation of one voltage by another. This cancellation resulted in sharp limits with no "giving" or leaking. When trouble did occur, it was usually immediately obvious because the high-gain amplifiers became overloaded.

For the most part, the rest of the equations were handled on the computer in a fairly routine manner. Except for provisions which allowed the operators to drop the pod from the plane, lower landing gears, shift the cg position, and those stated previously, reliance was mainly placed on dependable and familiar methods.

In tying analog equipment to the hardware, some difficulties of instrumentation were encountered since the flight control system accepted a 400-cycle amplitude modulated signal rather than a dc signal. These inputs were shown in Fig. 1 as the information from the air data computer to the central unit assembly.

After some experience with the difficulties involved with modulators was gained, a method was used in which transmitting synchros, excited with a 400-cycle signal, were coupled directly to dc resolvers. With proper scaling, the computer variables were made to drive the resolvers and thereby position the flight system's synchros.

The information from the power control linkage package was taken from the arms of dc excited Helipots, which were coupled to the hardware, and fed into the computer as analog voltages.

These signals consisted of:

1) Right and left elevon position,
2) Throttle and throttle servo output,
3) Resolution surface output,
4) Stick position.

Tying the computer to the cockpit simulator presented a variety of problems; however, their solutions were all provided for in the simulator's original design. Actual instruments or close approximations to the instruments were installed on the flight panel in order to give the pilot as realistic a presentation of his flight information as possible.

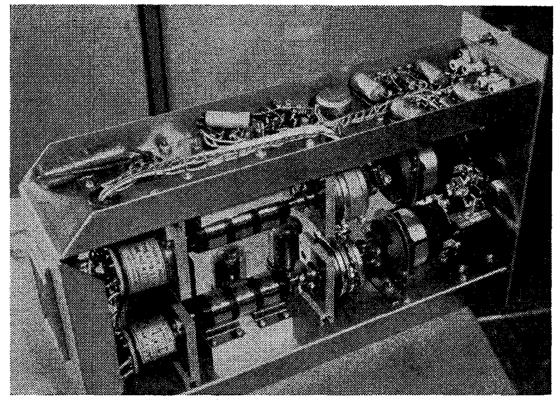

Fig. 8—Cockpit servo unit.

Some indicators were simulated simply by altering the face of a microammeter. Instruments having a "long scale," 250-degree rotation of the needle were preferred. Those used in this project were Hickok 500 microammeter, some with zero at the left and some with zero at the center.

The artificial horizon was especially complex and presented special problems. Because no way was devised to simulate this instrument, a real artificial horizon was purchased from Lear, Inc., and adapted for the specific usage.

Nine of the instruments chosen for the pilot's panel were driven by synchro repeaters (Fig. 8). Servo units, driven by signals from the analog computer, were built to position a synchro transitter, which in turn controlled the cockpit instrument, a synchro repeater.

Components were selected to give adequate performance at a reasonable cost. The Kearfott R-110 motor was chosen because it was powerful enough and quite small, although not small enough to be in the expensive miniature class.

All servos, except one, the altimeter, revolve one revolution or less, so one-turn follow-up pots were used. A type-J Helipot with its shaft extending front and back was selected. The motor, gear box, follow-up pot, and synchro were mounted colinearly to save space, to reduce cost, and to improve accuracy. If it had not been possible to arrange these components in a line, it would have been necessary to use idler gears to transmit torque around 90-degree corners, thus losing accuracy and space and increasing cost.

Magnetic amplifiers were used for power amplification to drive the motor since they are compact, efficient, and inexpensive. They controlled the flow of power from the power line instead of the flow being furnished from an expensive rectified power supply and thereby sharply reduced the necessary size of the dc power supplies. The Kearfott R-601 magnetic amplifier was chosen because of its small size, simple control circuits, and low cost. Its response was good up to 20 cps, which was sufficient for the instruments. Also, this cutoff "corner" frequency of 120 radians was safely remote from the motor cutoff