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A PRELIMINARY SYSTEMS STUDY
OF INTERFACE EQUIPMENT
FOR DIGITALLY PROGRAMMED FLIGHT SIMULATORS

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PREFACE

This report summarizes all work conducted by the Wichita Division of the Boeing Company under Task I of Contract NAS 2-5524, "Design for the Simulation of Advanced Aircraft". The National Aeronautics and Space Administration Technical Monitor was Mr. John C. Dusterberry of the Simulation Science Division. The Boeing Company Project Leader was Mr. C. Rodney Hanke of the Stability, Control and Flying Qualities Organization.

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SUMMARY

Five areas of a Supersonic Transport flight simulator are investigated.

1. Six techniques of direct digital drive are examined. These techniques are classified as quasi closed-loop, closed-loop and open-loop systems. The applicability to a Supersonic Transport simulation and the availability of each system is given.
2. The frequency response and operation of eight SST instruments are given. Feasibility of direct digital drive for these instruments is discussed.
3. Interfacing of cockpit controls with the digital computer by means of analog-to-digital converters, encoders and synchro-to-digital converters is discussed.
4. Supersonic Transport moving base simulator data recording requirements are given A comparison is made between analog and digital strip chart recorders for use in an all digital simulation.
5. Suggestions for configuring a project engineer's console are made by Boeing engineers with experience on moving base flight simulators.

INTRODUCTION

The purpose of this study is to provide preliminary information on:

1. Methods of driving simulator instrument displays with direct digital inputs.
2. Methods of interfacing cockpit controls with digital computers.
3. Data recording systems.
4. Important characteristics of project engineer's consoles.

Special emphasis is given to the following items:

1. Use of direct digital drive for all of the simulator flight instruments selected for this study.
2. Reliability of direct digital drive for positioning instruments with tolerable errors.
3. Feasibility of direct digital drive equipment from an economic viewpoint.
4. Compatibility of the instrument display system frequency response with aircraft instrument requirements.
5. Ability of direct digital drive to simplify the link between the motion cab and controlling computer.
6. Validation of instrument indications where direct digital drive hardware is employed for operating diagnostics.
7. Adaptibility of direct digital drive for use with instrument displays of the Supersonic Transport (SST).

Simulator interface requirements are based on the following ground rules:

1. The simulator instrument response characteristics are compatible with the current SST instrument response requirements.
2. The simulation uses only digital computations.

The following flight instruments are considered for this study:

1. EADI (Electronic Attitude Director Indicator)
2. HSI (Horizontal Situation Indicator)
3. Moving Map Display
4. Calibrated Airspeed Indicator
5. Altimeter
6. Vertical Speed Indicator
7. Machmeter
8. Engine Thrust Indicator

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NOMENCLATURE

a	Switching Function
A-D	Analog-to-Digital
AFCS	Automatic Flight Control System
c	Command
D-A	Digital-to-Analog
DDD	Direct Digital Drive
DME	Distance Measuring Equipment
D-S	Digital-to-Synchro
EADI	Electronic Attitude Director Indicator
HSI	Horizontal Situation Indicator
Hz	Frequency, Hertz
INS	Inertial Navigation System
M	Motor
ms	Millisecond
n	Number
S	Switch
S-D	Synchro-to-Digital
SST	Supersonic Transport
V	Voltage
VHF	Very High Frequency
VOR	VHF Omni Range
θ	Shaft Rotation Angle

DIRECT DIGITAL DRIVE CONCEPTS

Flight simulators which use digital computers to solve the aircraft equation of motion require interface equipment to link the outputs of the digital computers to the inputs of the analog flight instruments. A block diagram of such a system is shown on Figure 1. This system uses conventional digital-to-analog converters with instrument servos and synchro converters to link the instruments in the flight simulator cab with the digital computer outputs. The pilot's input signals into the equations of motion programmed on the digital computer are generated by use of position potentiometers on the flight controls. The flight control analog information is input into the digital computer equations of motion through multiplexer and analog-to-digital conversion equipment.

The complexity of interface equipment is one of the primary causes of simulator down time and overall system computation errors. Positioning the flight instruments with direct digital drive will simplify the present interface equipment.

Direct digital control concepts for simulated aircraft instruments are categorized as quasi closed-loop systems, closed-loop systems and open-loop systems. The open-loop system can be implemented with parallel or serial inputs, however, systems with serial inputs are slower.

SIMULATOR INTERFACE

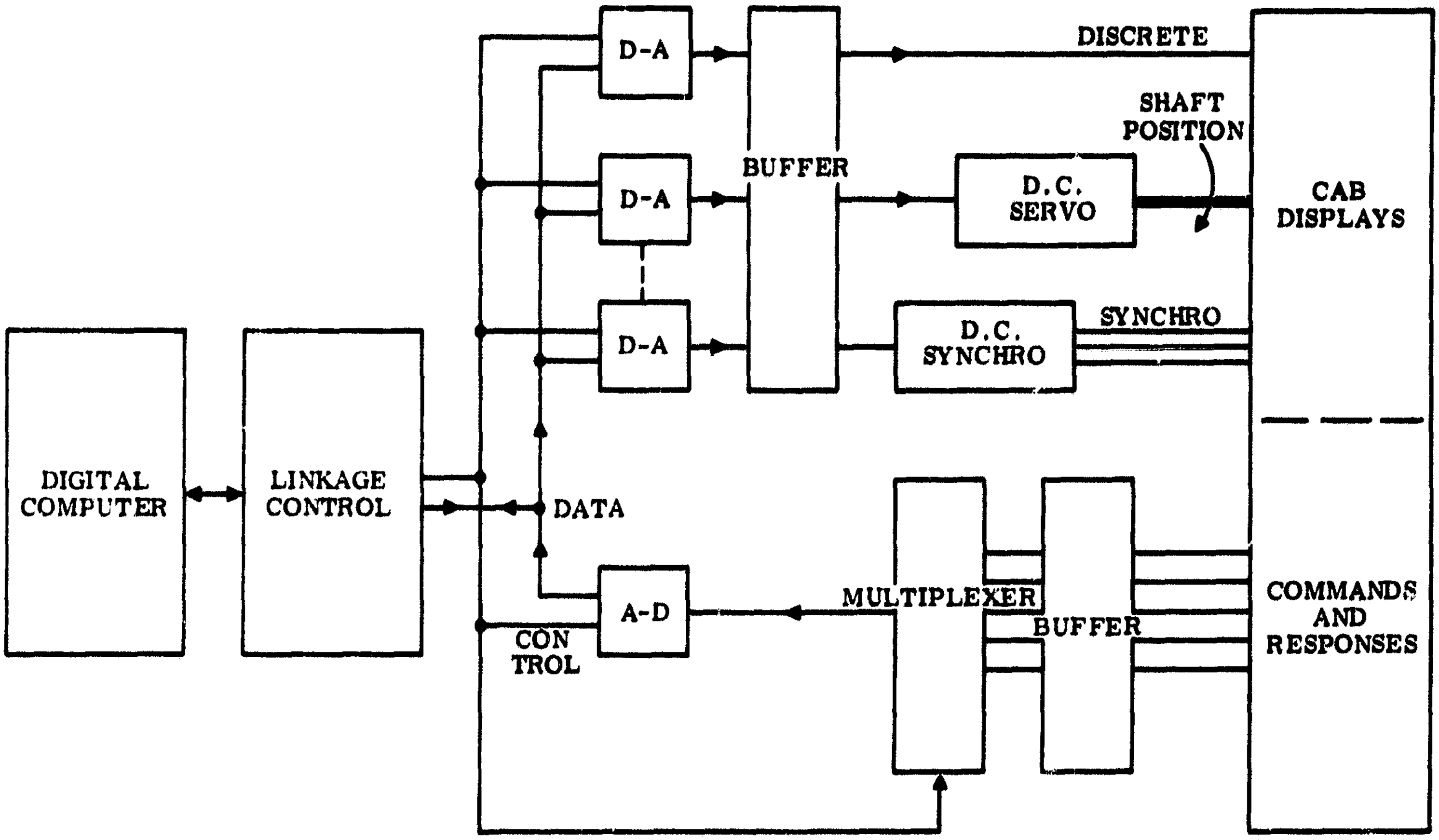


FIGURE 1

QUASI CLOSED-LOOP DIRECT DIGITAL CONTROL

The Simulation Equipment Group of the Boeing Company Seattle has developed a direct digital drive system to provide improved interface equipment accuracy and reliability for SST simulations. Figure 2 is a block diagram illustrating how this method operates. The output of the computer is distributed to the digital drive systems through an address decoder. This is a quasi closed-loop system since an error signal is generated by comparing the computer data and the up/down counter output. The up/down counter obtains its input from the motor control input instead of the shaft output. The comparator examines the inputs from the jam register and the up/down counter. The jam register is a conventional parallel register and only one connection is demanded of the computer. All trigger inputs are connected to a common pulse line which is operated by a pulse from the address decoder. If a discrepancy exists in the comparator, a pulse generator is started to operate the up/down counter. Decision making circuits in the comparator control the up/down counter. If the comparison is low the counter will add and if high, the counter will subtract. As a result the up/down counter seeks a null with the jam register. The pulse generator is controlled by dual mutually exclusive gates which allow either normal operation or mechanical zeroing. The output of the pulse generator is fed to a motor controller which interfaces the direct digital drive logic and the stepper motor. It accepts serial pulse inputs and translates them to properly sequenced current pulses which energize the windings of the stepper motor. The stepper-motor, when energized by DC voltages in a programmed manner, indexes the analog needle in given angular increments. The angular displacements are either clockwise or counter clockwise. The direction of the motion is determined by the sequence in which the windings are pulsed. The up/down counter provides a record of the last displayed contents of the counter and the motor has only to step the difference to the most recent up-dating. Variable reluctance four-phase stepper motors are used in this direct digital drive system because of the ease with which small angular steps are obtained and because of their ability to run at high pulse rates. The Kearfott (cm 40192001) stepper motor is used in the SST direct digital drive instrument and is capable of 500 steps/sec. with an inertia load of .85 gmcm^2. Stepper motor performance for the Boeing SST simulation is given in Appendix A.

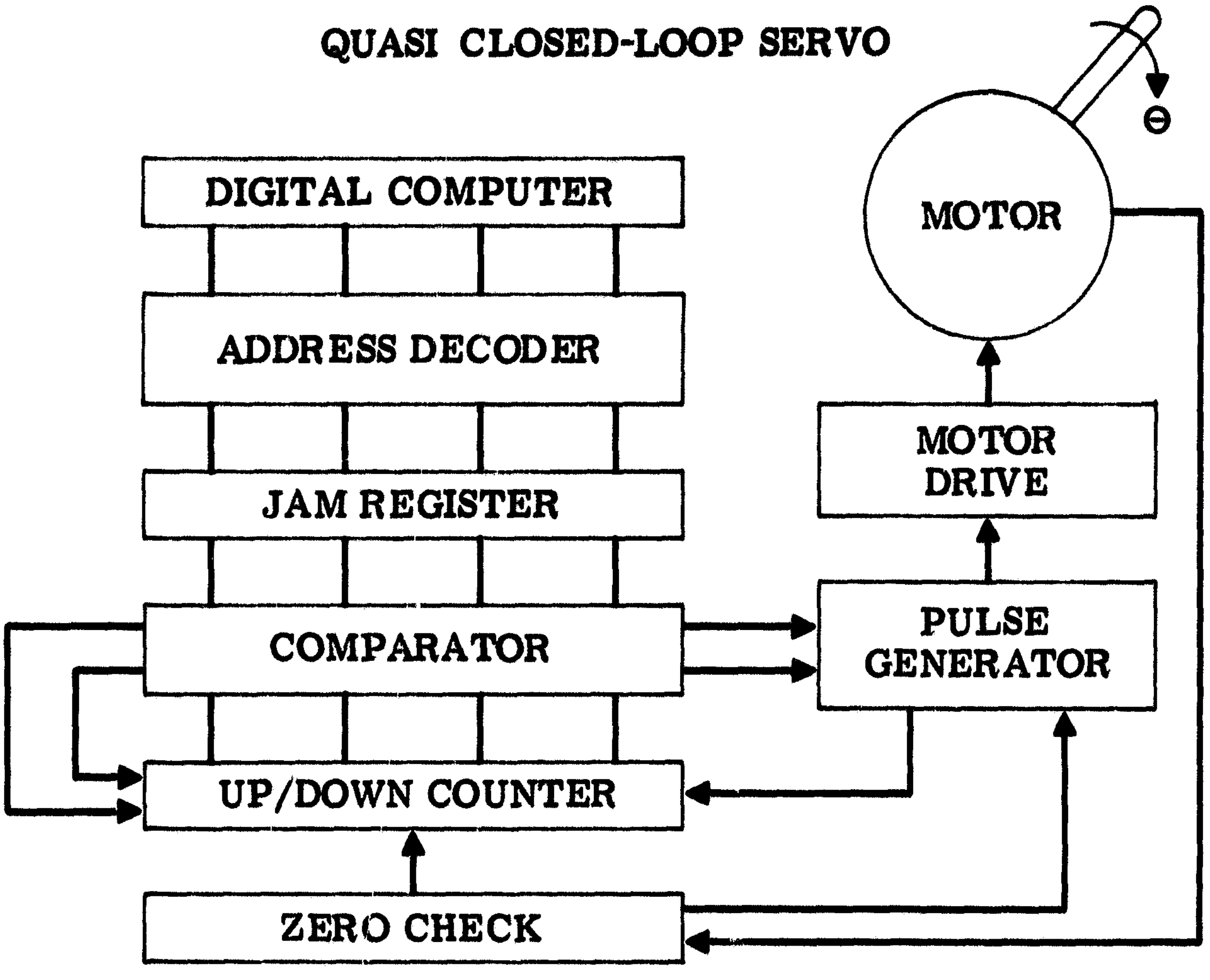

QUASI CLOSED-LOOP SERVO

FIGURE 2

Because this system operates incrementally, there is a possibility of missing a step and generating a permanent zero offset. A zeroing device is incorporated to eliminate any offset and to provide a means of setting up an initial datum. The zeroing mechanism consists of a small hole drilled through all of the gears that move when the motor is stepped. A lamp shines through the path and the light impinges on a photocell giving an electrical signal when the holes are aligned. This signal uniquely defines the zero position only at the mechanical zero position when there is coincidence between all the gears.

The quasi closed-loop system has been fabricated and tested by the Boeing Company in Seattle. Photographs of the instrument now in operation are shown in Figures 3 and 4.

**ALTIMETER
WITH QUASI CLOSED-LOOP
DIRECT DIGITAL DRIVE**

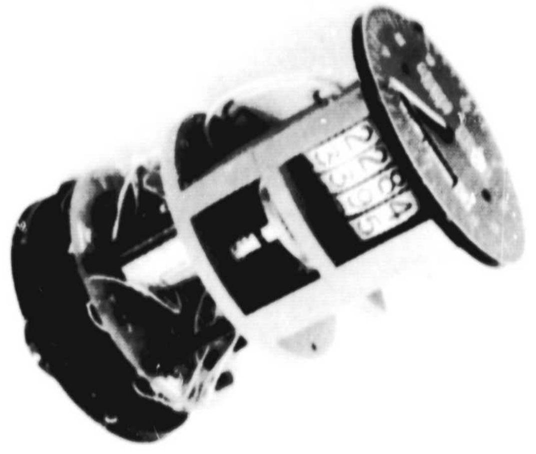


FIGURE 3

**ALTIMETER DISPLAY OF
QUASI CLOSED-LOOP DIRECT
DIGITAL DRIVE INSTRUMENT**

FIGURE 4

CLOSED-LOOP DIRECT DIGITAL CONTROL

Closed-loop direct digital control can be implemented with continuous position feedback or incremental position feedback.

DIGITAL POSITION FEEDBACK

The continuous position feedback concept shown in Figure 5 obtains its feedback from a shaft encoder or a synchro to digital converter mechanically coupled to the analog needle indicator. The address decoder opens the gates as a function of the device busy signal to allow the strobe pulse to jam the binary position information from the data channel into the input register. A digital comparison is made of the control position data and the shaft encoder feedback to determine which direction the motor shaft should rotate. The comparator commands the stepper motor up or down to achieve an equal condition from the comparator. Further stepper pulses are blocked from reaching the motor unit, which stops further indicator movement.

Manual control of instrument select and data input provides a means of checking instrument operation. The external select simulates a command from the computer as device select. Test data can be set in from manual switches and jam loaded by means of a test strobe.

The electrical and mechanical zero are also manual inputs for rezeroing the instrument and for calibration procedures. The zeroing logic essentially takes control away from the comparator except for the direction the motor should rotate. The mechanical zero sets the zeroing logic in the motor control unit for detecting and correcting all possible error combinations with feedback from the photo cell being the null condition. Essentially the electrical zeroing consists of resetting the input register to zero and allowing the position system to operate in a normal manner. The use of the electrical zero is sufficient in a closed-loop system since shaft position is sensed and compared to the zero reference. If economic and space considerations are critical, the redundant mechanical zero can be omitted.

A flip flop is set indicating a device malfunction if the time required for a zeroing operation exceeds a predetermined maximum. For example the time required to position indicators separated by 180 deg. (maximum response time) for .5 deg per step resolution is $\frac{180}{(500 \text{ steps/sec}) (.5 \text{ deg./steps})} = 720$ ms.

If an update cannot occur in this maximum time, a device flag is set. Then the device flag indication can interrupt the computer program after the current operation cycle. The maximum zeroing time can be adjusted to accommodate estimated maximum zeroing time.

DIGITAL POSITION FEEDBACK

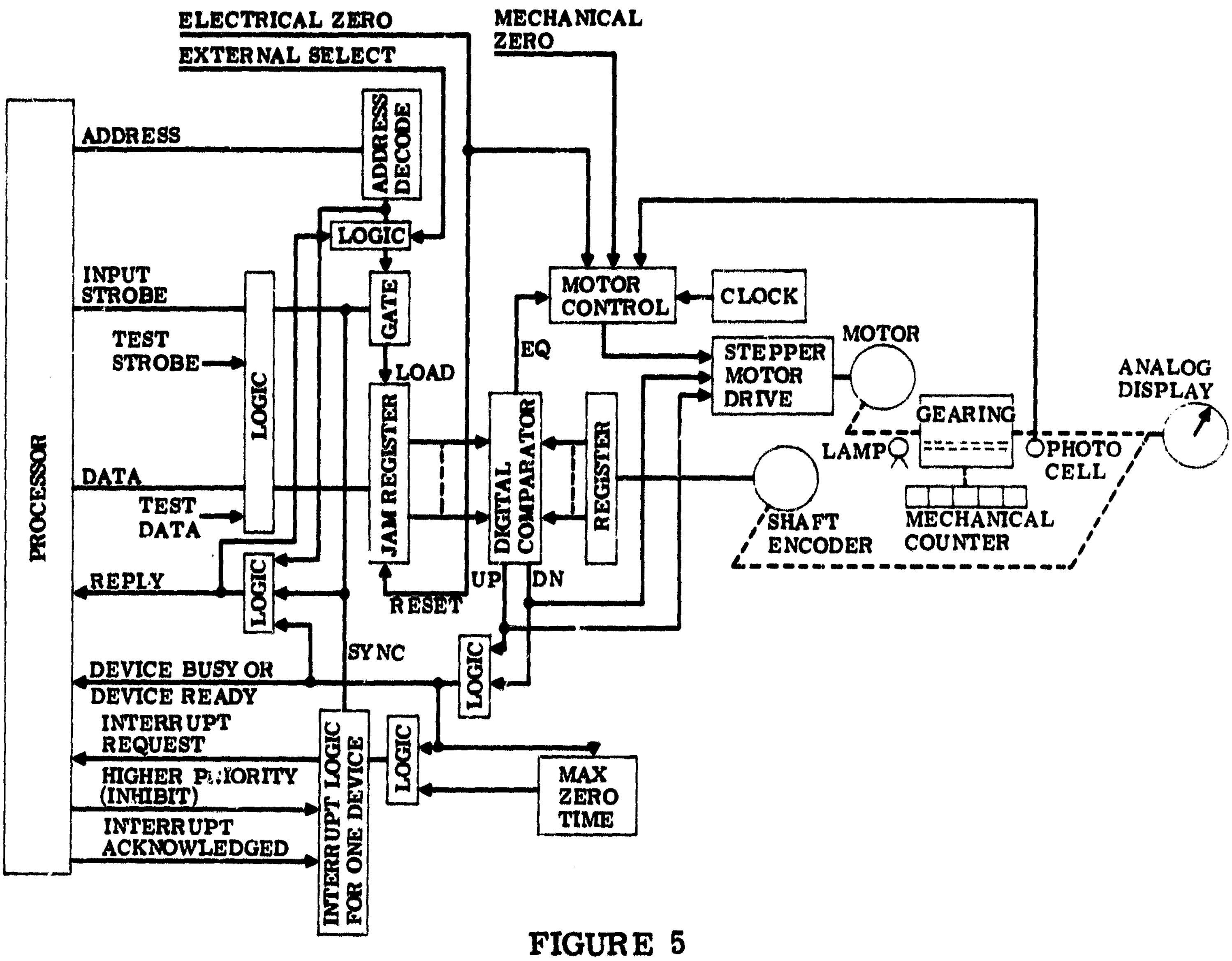


FIGURE 5

INCREMENTAL FEEDBACK

The incremental feedback method has fewer logic elements and is less expensive than the continuous position feedback method. A simplified block diagram of the system is shown in Figure 6.

An up/down counter is utilized in the error detecting circuit of both the incremental feedback and the quasi closed-loop system. The feedback element for the incremental system consists of a disc with calibrated slots and a photo cell for detecting the actual motion of the shaft. Each step command is compared to a step feedback for an error determination. This approach alleviates the 360 deg. - 0 deg. ambiguity problems that occur with the use of shaft position feedback from an encoder or synchro to digital converter. If the motor skips a step, the rotation is sensed at the motor shaft and the offset error is corrected.

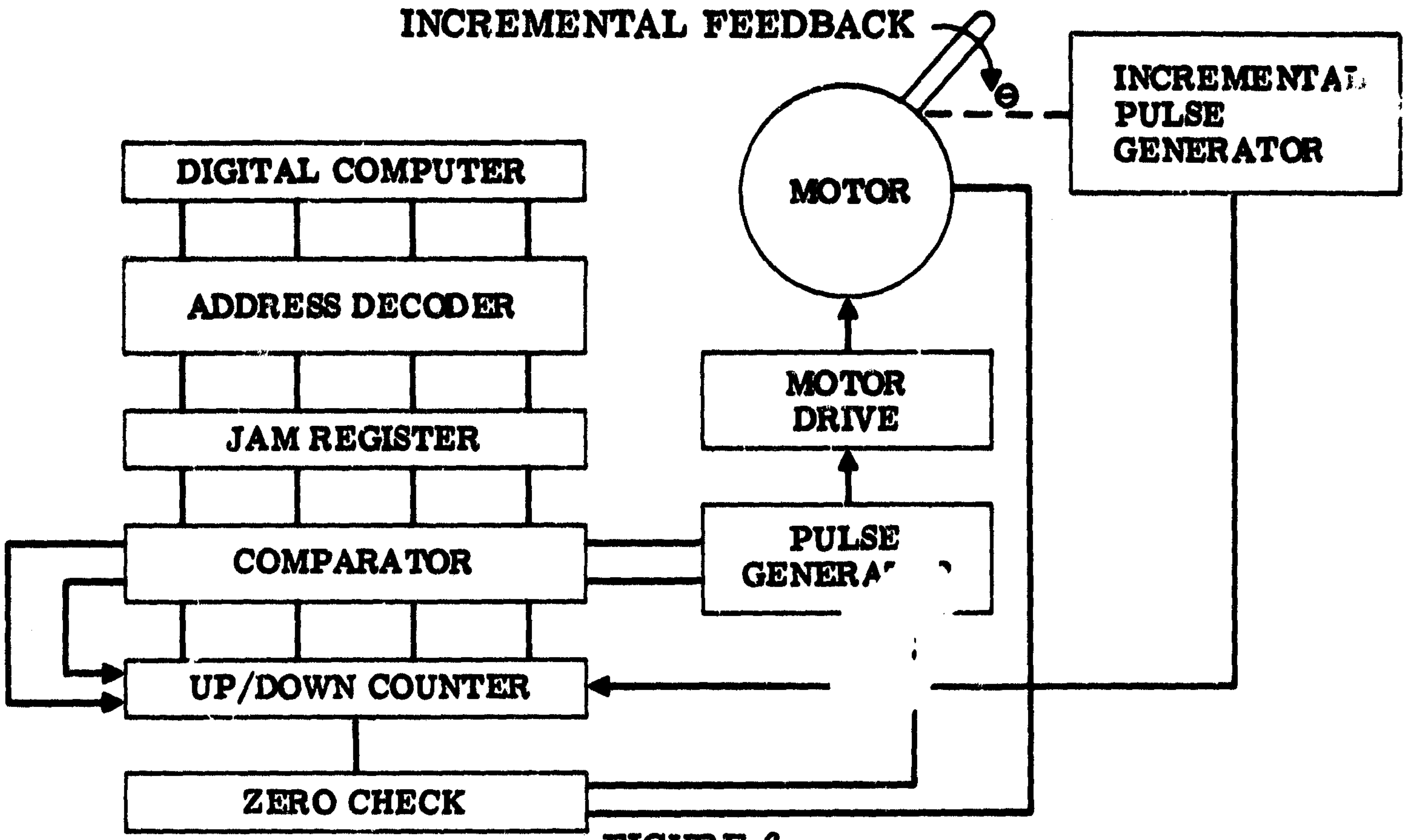
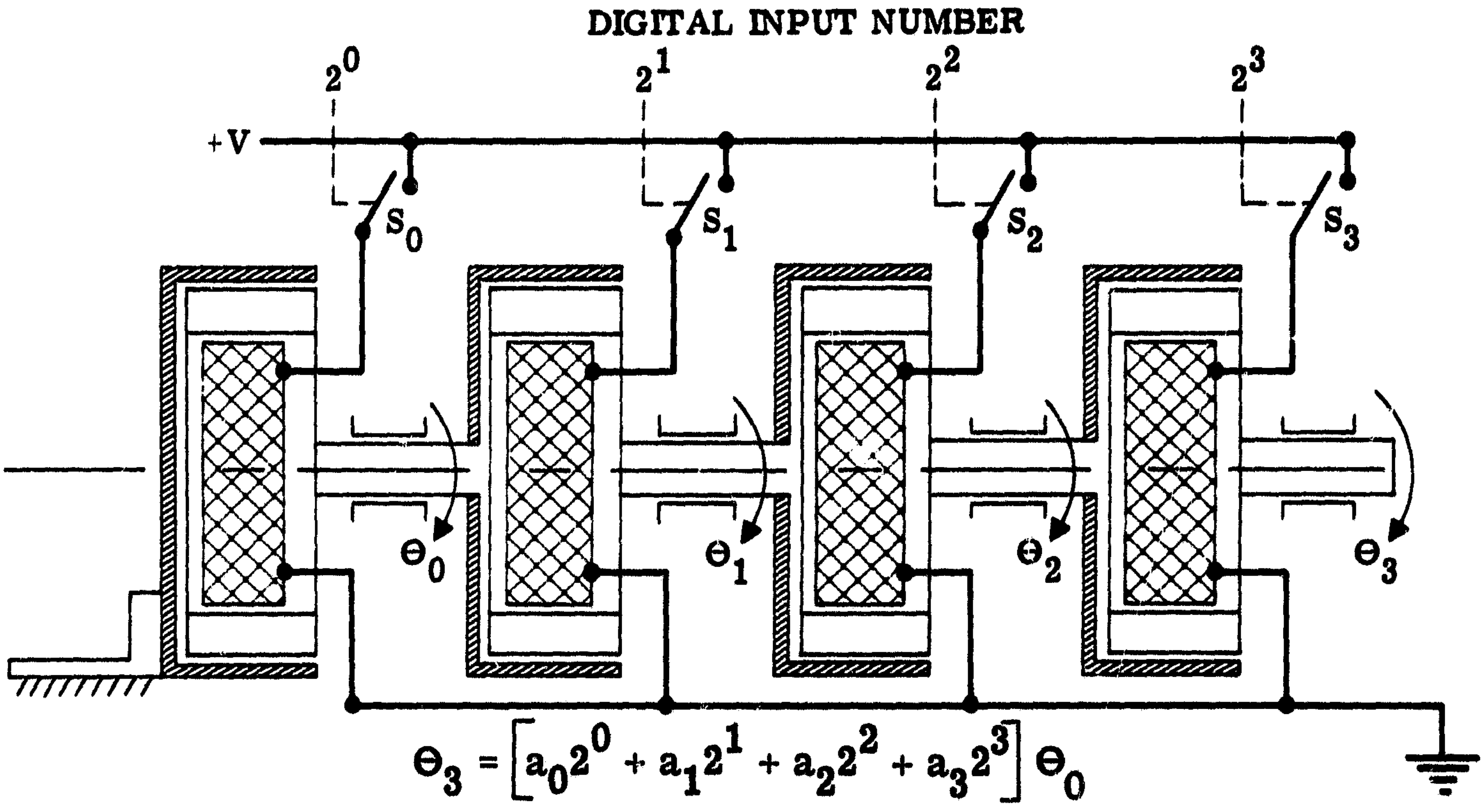


FIGURE 6

PARALLEL DIRECT DRIVE



$$\Theta_3 = \left[a_0 2^0 + a_1 2^1 + a_2 2^2 + a_3 2^3\right] \Theta_0$$

FIGURE 7

OPEN-LOOP DIRECT DIGITAL CONTROL

Open-loop parallel direct digital control methods mechanically add a combination of step inputs to give the total shaft excursion. There are several methods of implementing this basic theory.

PARALLEL DIRECT DRIVE

The parallel direct drive principle is illustrated by the solenoid system shown in Figure 7. For this system, the output shaft position (θ) is given by:

$$\theta = \left[a_0\, 2^0 + a_1\, 2^1 + \quad a_2\, 2^2 + \cdots + a_n\, 2^n \right] \theta_0 \qquad (1)$$

where a_n = 1 if nth switch is closed

a_n = 0 if nth switch is open

and θ_0 is the step input

Only the stator of the solenoid with the least significant excursion ($a_0\, 2^0\, \theta_0$) is fastened to a reference surface. The stators of the other solenoids are tied to the rotors of the lesser-significant solenoids. An electrical input, to any one solenoid displaces the rotor with respect to the stator by a constant amount. The magnitude of this displacement is determined by the position of an accurately located mechanical stop. Mechanical addition of the n input steps, $2^0\, \theta_0, 2^1\, \theta_0$, etc., is accomplished automatically with the mechanical interconnection of "n" solenoids. For example, consider a four bit digital input such that switches S_0 and S_2 are closed and switches S_1 and S_3 are open.

$$\begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 1 \\ 0 \end{bmatrix}$$

Set $\theta_0 = 3$ deg.

Then by equation (1) $\theta_3 = (2^0 + 2^2)\, 3 = 15$ deg.

The rotor of the least significant solenoid (θ_0)deflects (2^0) 3 or 3 deg. The stator of solenoid No. 1 is rotated 3 deg. by the shaft position of solenoid No. 0. The rotor of solenoid No. 1 is not rotated relative to its solenoid (switch S_1 open) and therefore, the shaft of solenoid No. 1 is 3 deg. The stator of solenoid No. 2 is positioned with the shaft of solenoid No. 1 and is equal to 3 deg. The rotor of solenoid No. 2 is deflected $(2^2)3$ or 12 deg. with respect to its own stator. Therefore, θ_2 is equal to 3 deg. + 12 deg. or 15 deg. Since switch S_3 is open, θ_3 is also equal to 15 deg.

PARALLEL GEARED DRIVE

The open-loop servo method for positioning an output shaft from parallel inputs is shown in Figure 8. This method uses parallel drives to position the output shaft through a series of differentials. The 2:1 differentials provide the binary division between the least significant bit and the most significant bit. The output shaft position (θ_{op}) for this system is expressed as:

$$\theta_{op} = \left[a_0\, 2^{-(n-1)} + a_1 2^{-(n-2)} + a_2 2^{-(n-3)} + \cdots + a_{n-1}\, 2^0 \right] \theta_c \qquad (2)$$

where n = number of switches in the system
a_n = 1 if the nth switch is closed
a_n = 0 if the nth switch is open
and θ_c is the step input

As an example, consider the same four bit digital input as used for the example of solenoid servo system and set $\theta_c = 24$ deg.

The switches S_0 and S_2 are closed and switches S_1 and S_3 are open, therefore

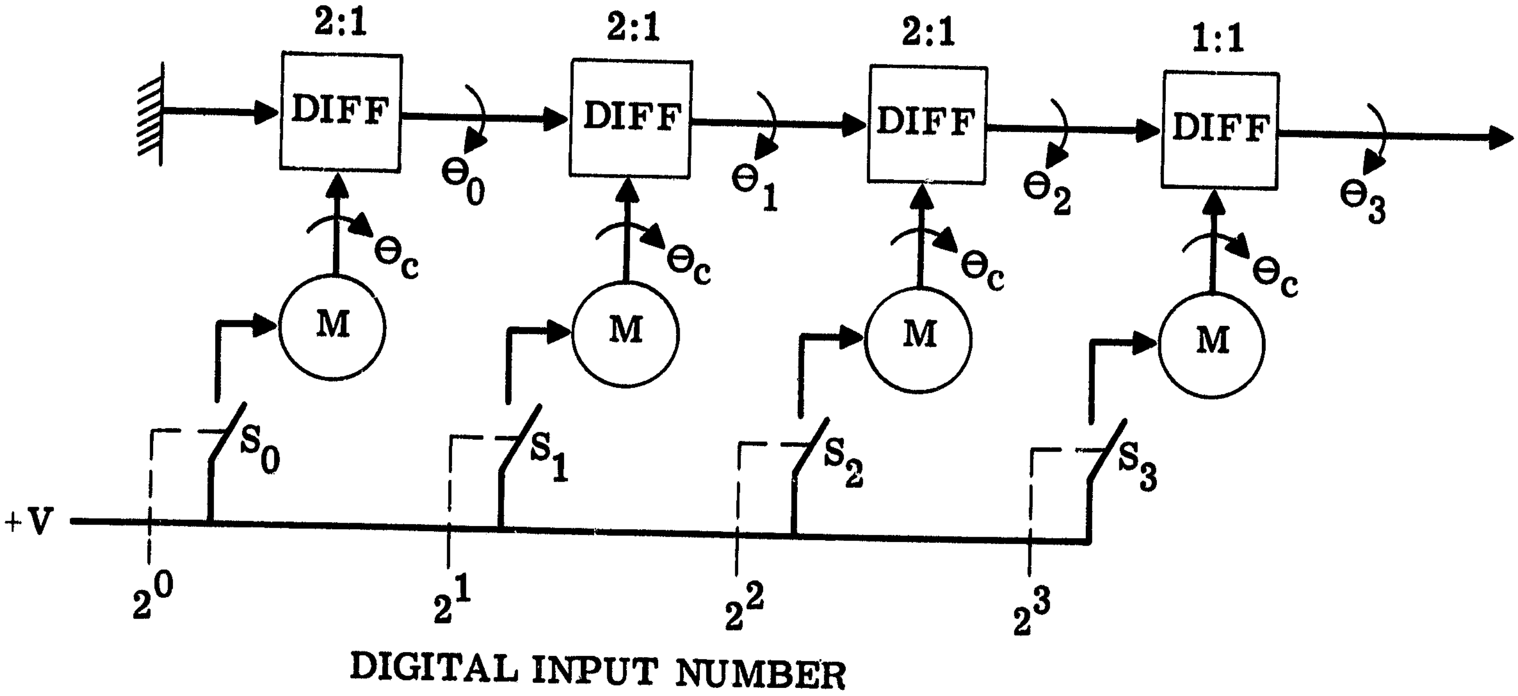
$$\begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 1 \\ 0 \end{bmatrix}$$

By closing only switch S_0, θ_0 = 12 deg.
θ_1 = 6 deg.
θ_2 = 3 deg.
θ_3 = 3 deg.

By closing only switch S_2, θ_2 = 12 deg.
θ_3 = 12 deg.

The total output shaft position with both switches S_0 and S_2 closed is θ_3 = 3 deg. + 12 deg. + 15 deg. or by equation (2) $\theta_3 = (2^{-3} + 2^{-1})\, 24 = 15$ deg.

PARALLEL GEARED DRIVE



$$\Theta_3 = \left[a_0 2^{-3} + a_1 2^{-2} + a_2 2^{-1} + a_3 2^{0} \right] \Theta_c$$

FIGURE 8

Smaller unit step divisions provide more resolution but require more rapid updating to provide equal slewing speeds.

PARALLEL REDUNDANT DRIVE

A direct digital drive system which uses redundant controls and separate drives on the digital readout and the analog needle indicator is shown in Figure 9. The only moving part in each digital indicator is the readout drum, which is an integral part of a rotating magnetic assembly. Positioning of the readout drum is controlled by energizing combinations of windings in the indicator's fixed stator assembly. Binary data are input to digital-to-synchro conversion unit which drives a torque receiver to position the analog needle indicator.

PARALLEL REDUNDANT DRIVE

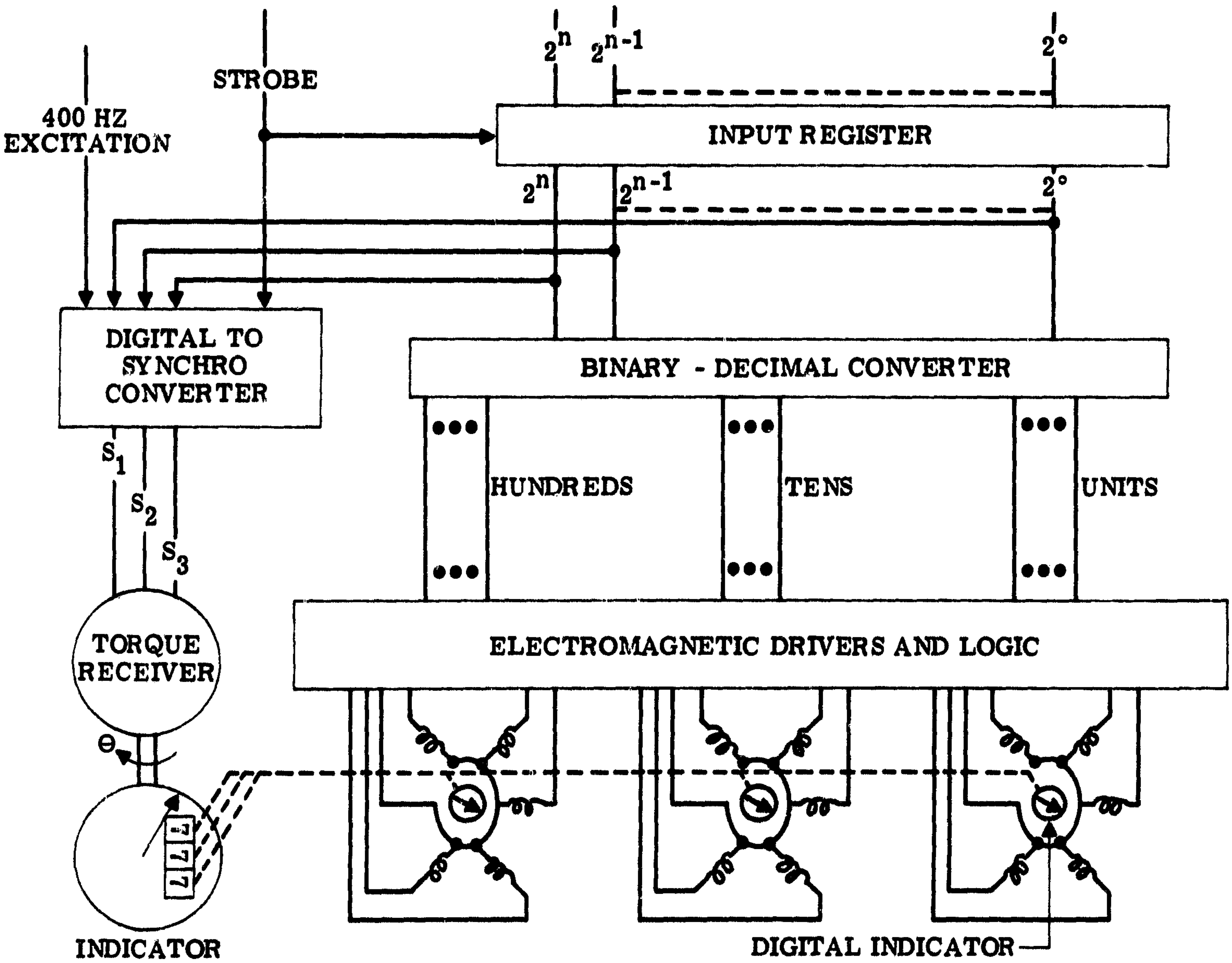


FIGURE 9

The parallel redundant drive system compensates for non-linear scale factors between two redundant instrument readouts such as the digital readout and the analog needle readout of the SST airspeed indicator. Compensation of non-linearities between two redundant displays is usually programmed in the digital computer. The parallel redundant direct digital drive instrument requires two input registers, one for the electromagnetic indication and the other for the digital to synchro converter. The possibility exists that the readouts can display contradictory information due to malfunctions in one system or the other.

DIRECT DIGITAL DRIVE OPERATING CHARACTERISTICS

Table 1 shows results of rating six direct digital drive concepts according to ten desirable qualities.

TABLE 1
COMPARISON OF
DIRECT DIGITAL DRIVE CONCEPTS

RATING 1 = EXCELLENT, 2 = VERY GOOD, 3 = GOOD, 4 = FAIR, 5 = POOR

SYSTEM / QUALITY	OPEN-LOOP			QUASI CLOSED-LOOP	CLOSED-LOOP	
	PARALLEL GEARED	PARALLEL DIRECT.	PARALLEL REDUNDANT		POSITION FEEDBACK	INCREMENTAL FEEDBACK
SPEED	1	1	2	2	3	3
RELIABILITY	3	3	1	2	1	1
NOISE LEVEL	5	5	3	2	2	2
COMPACTNESS	5	5	3	1	3	2
EASE OF PROGRAMMING	2	2	2	3	3	3
INSTRUMENT VALIDATION CAPABILITY	5	5	5	4	2	1
RESOLUTION	4	4	3	2	2	2
SIMPLICITY	4	4	3	2	2	2
FLEXIBITLIY	4	4	2	3	3	3
COST	5	5	3	1	2	2

Digital instruments for high performance aircraft simulation are not available as standard units. The development and fabrication cost for a small number of digital instruments would exceed the cost of analog instruments by several times.

The parallel geared drive and the parallel direct drive advantage is speed and simplicity for small binary words. The complexity of gearing to obtain instrument accuracy and the noise emitted from the gearing, in the confines of the simulated cockpit, prohibits use of these systems. The parallel redundant system displays numerals for one digit positions of the readout register. They are independent of any other digit positions. The advantages are:

1. A rapid set up of a new display value when compared with counters. The readout register response time depends only on the response time of any one decade device in the register.
2. More flexibility. The same decade device can be used in almost all readout registers regardless of the number of digit positions or range of values required.

A disadvantage is:

1. A separate driving circuit is generally required for each digit position, making the device expensive in

initial cost and in interfacing costs to the computer. A signal or sequence of signals is sent to the device, and its position at the end of this is assumed to visually present a particular value.

The dual parallel system does not lend itself to instrument validation for operating diagnostics because of the open-loop operation. However, the flexibility of the parallel redundant system allows the digital computer to program the input registers differently to allow for nonlinear analog dial indications.

The quasi closed-loop and closed-loop systems use counter devices. The counter devices are mechanical indicators which display the numerals for two or more digit positions of a readout register with gearing between the digit positions and a single drawing mechanism. The advantages are:

1. Output quantities from the computer to the counter may be direct binary.
2. Only one driving device and circuit is required for a readout register.
3. They are generally less expensive than most other information readout devices or at least very competitive in price.

The disadvantages are:

1. Slewing time problems. Counter slewing takes time and limits the operating speed of the system displays.

The counter devices are not very flexible and separate designs must be used for the display of angles, time and distances. (Slewing time problems are reduced by driving the counter with the high-speed stepper motor.

The quasi closed-loop systems provide instrument diagnostic flags due to the error detection designed into the instrument feedback logic.

The reliability of the instrument reading is increased due to monitoring of the instrument by the computer with accompanying error notification. The closed-loop systems possess a conservative speed of 500 steps/sec. and provide simplicity and correlation of dial and digital readouts due to the common drive system.

SST INSTRUMENT ENVIRONMENT

The SST cockpit motion is well defined with a mathematical model containing 10 structural degrees of freedom and 6 rigid body degrees of freedom. The structural modes are represented by coupled linear second order equations. The modes are lightly damped with discrete natural frequencies between 1 and 10 Hz. The rigid body frequencies (Dutch roll and short period) are approximately .2 to .4 Hz. No less than four structural modes can be used to meaningfully describe the SST cockpit motion. The frequency content of a four structural mode model of the SST has a bandwidth of 1 to 4 Hz.

High frequency signals are input to some SST instruments such as the accelerometer. Other inputs which drive the airspeed, altitude, and Machmeter instruments do not contain the structural frequency components. However, all of the instruments in the cockpit are physically subjected to the same potential high frequency motion created by disturbing the elastic airframe modes. All equipment mounted on the moving base simulator must be designed for operation in a high frequency, high acceleration environment.

DIRECT DIGITAL DRIVE FOR SST SIMULATOR INSTRUMENTS

The Boeing Company has not completely determined which flight instruments will be used in the SST. The instrument performance requirements and specification given in this section are preliminary and may not correspond to the final instrument requirements for the aircraft. The existing requirements of proposed instruments were studied to determine if direct digital drive of some or all of these instruments is feasible.

ELECTRONIC ATTITUDE DIRECTOR INDICATOR (EADI)

The EADI display is shown in Figure 10. EADI instruments are mounted on both the captain's and first officer's instrument panels. The display presents information on the face of a cathode ray tube with electronically generated symbols. A reference airplane display in relation to an artificial horizon provide pictorial flight information to the pilot. The following parameters are displayed on the EADI:

1. Pitch Attitude
2. Roll Attitude
3. Pitch Command
4. Roll Command
5. Speed Error
6. Localizer Deviation
7. Glide Slope Deviation
8. Radio Altitude
9. Flight Path Angle
10. Flight Path Acceleration
11. Minimum Decision Altitude

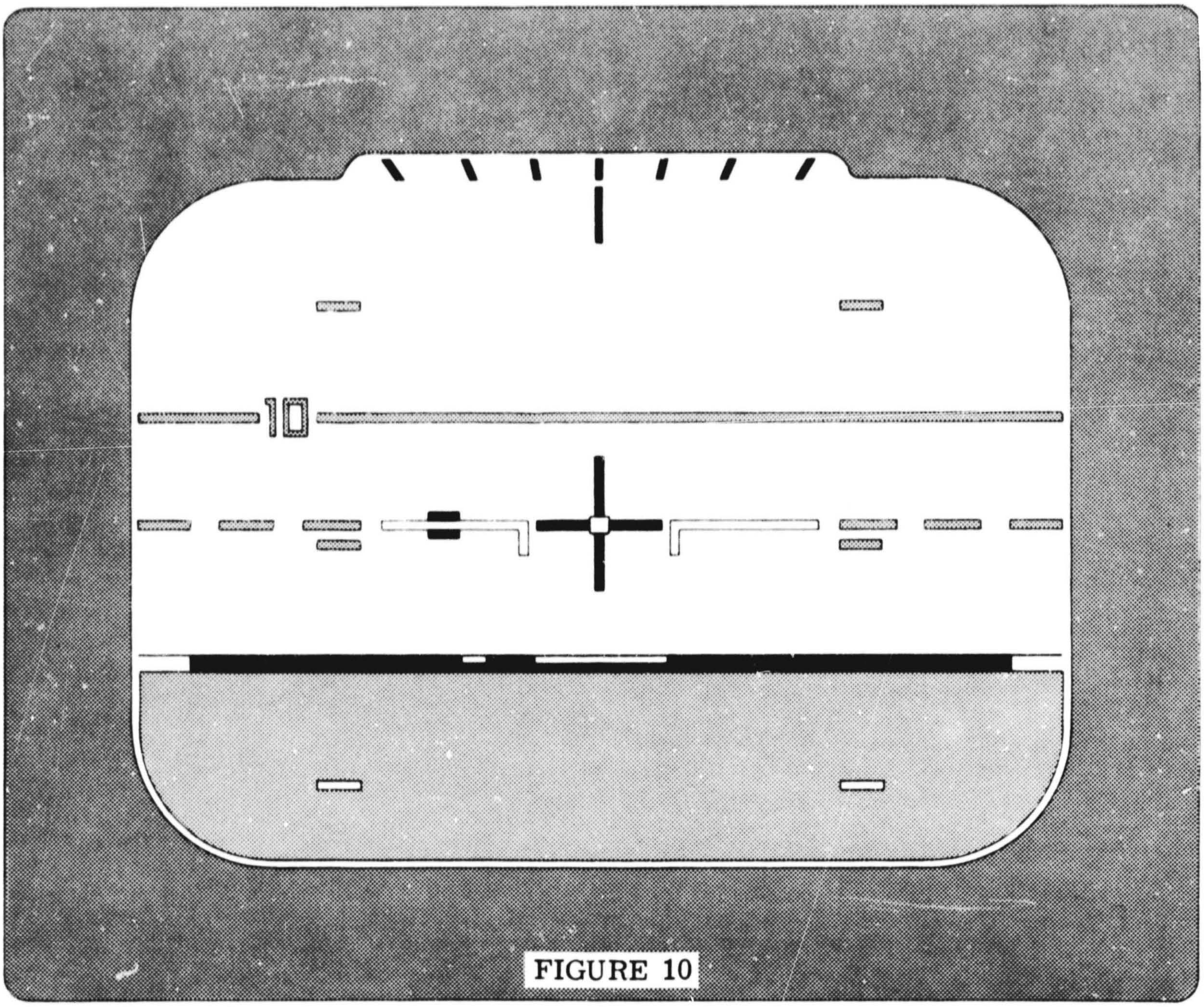


FIGURE 10

The EADI can also be used as a TV monitor utilizing a camera located under the body. The display parameters, ranges, and sensitivities of the EADI used in the Boeing fixed-base simulator are shown in Table 2.

TABLE 2
EADI DISPLAY IN BOEING FIXED-BASE SIMULATOR

Display	Range	Sensitivity
Pitch Angle	+ 17" or + 100	0.17" per degree pitch
Roll Angle	+ 360	1 per degree roll (10 per index marking)
Pitch Flight Director	+ 1" or + 10	0.1" per degree
Roll Flight Director	+ .8" or + 20	0.04" per degree
Speed Error	+ 1.4" or + 20 knots	0.07" per knot
Radio Altitude	1000 ft.	1 ft/foot radio altitude
Glide Slope Deviation	+ 0.88" or + 0.7	1" per 0.2 or 1/5 dot
Localizer Deviation	+2.8" or + 0.56	0.44" per 0.35 or 1 dot
Flight Path Angle	+ 3.4" or 20	0.17" per degree
Path Acceleration	+ 2.82" or + 11.3 ft/sec	0.25" per ft/sec

EADI instrument scale factors are listed in Appendix B. The EADI instrument for the simulator and the proposed Norden EADI for the aircraft use analog inputs.

The following lists the advantages and disadvantages of analog-digital signals within the EADI. The EADI system has been divided into two sections (the display unit and the interface) to simplify interpretation.

DIGITAL DISPLAY UNIT

Advantages

1. High accuracy and stability over full environment ranges
2. Resolution limited only by signal source and cathode ray tube display techniques.
3. Rectangular symbol motion require little signal processing.
4. Software changes allow display flexibility.

Disadvantages

1. Roll motion requires considerable signal processing
2. Volume and weight of processing circuitry is fairly high.
3. To take full advantage of the high resolution capability, high-speed logic is required. This, in turn, increases the total power consumption of the processing circuitry.

DIGITAL INTERFACE

Advantages

1. Information transfer does not involve loss of accuracy.

2. Only the transmission link is required for each signal source.

3. Readily adaptable to any multiplex system.

Disadvantages 1. Input sampling rate must be high enough to avoid objectional symbol stepping.

2. Unless all input equipment and the EADI use the same data clock, the interface must compensate for several different data rates.

ANALOG DISPLAY UNIT

Advantages 1. Rectangular and roll motion requires simple signal processing.

Disadvantages 1. Accuracy and stability are extremely difficult to maintain throughout the operating environment.

2. Resolution is limited by overall system bandwidth.

3. Little or no display flexibility once the system has been constructed.

ANALOG INTERFACE

Advantages 1. Analog input signals require little or no processing.

Disadvantages 1. Each analog input signal must be hard wired.

2. Not readily adaptible to a multiplex system.

3. Interface contributes a finite error to the ultimate display.

HORIZONTAL SITUATION INDICATOR (HSI)

The HSI is an integral part of the flight director system. This display shown in Figure 11 utilizes several data sensors to obtain the input information. These include the Azimuth Coupler, VHF Navigation, Distance Measuring Equipment, Automatic Flight Control Subsystem, and Inertial Navigation System. The HSI processes these data and furnishes the pilot information solving his navigational problem with a specific and unique solution based on triangulation. The following parameters are displayed on the HSI:

1. Radio/Nav. Selection Annunciator
2. Heading (True or Magnetic)
3. Annunciation of Type of Heading Information Displayed
4. Heading Failure Warning
5. Selected Heading
6. Selected Course (Or Desired Track Angle During Inertial Nav.)
7. Course Deviation (VOR, Localizer, or Inertial Cross-Track)
8. Navigation Failure Warning

9. Vor Ambiguity (To-From)

10. Glide Slope Deviation

11. Glide Slope Failure Warning

12. DME 1 Distance

13. DME 2 Distance

FIGURE 11

HORIZONTAL SITUATION INDICATOR DISPLAY

MOVING MAP DISPLAY

Map-type pictorial navigation displays and area-navigation procedures have been in operational use by the Air Defense Command for a decade and have beep proven feasible as primary flight instruments. The moving map display is being given consideration for use in the production of SST aircraft. The Hughes Aircraft Company moving map is under consideration along with Astronautics Corporation and others.

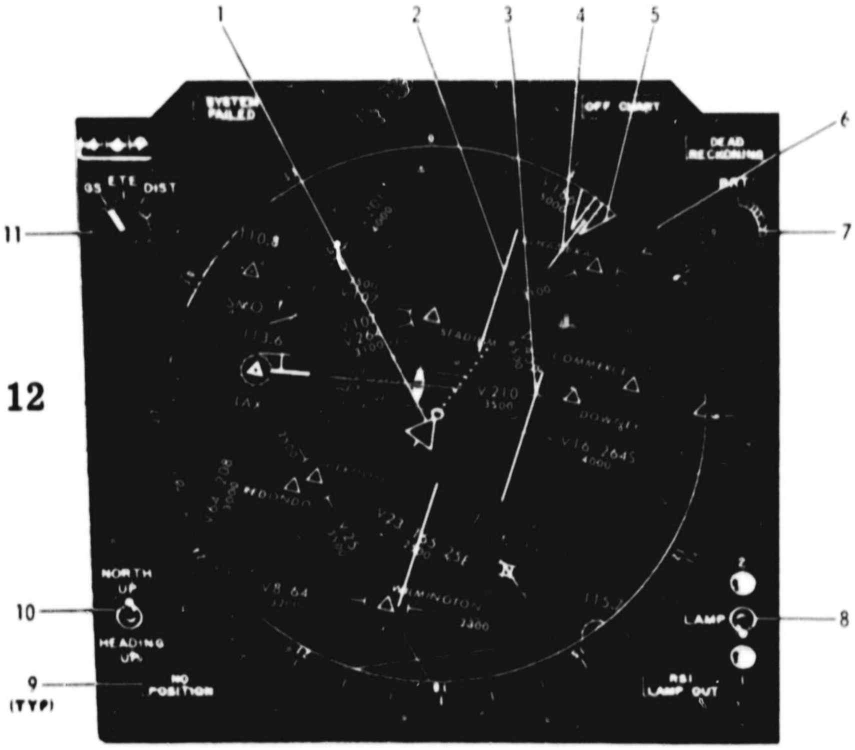


FIGURE 12

The Navigation Director display is an optical projection type of display which has a 7 inch viewing screen. Aircraft position is presented by computer controlled positioning of a navigation chart under an aircraft symbol located at the center of the display (1). In addition to aircraft position, the following display features are provided:

2 Route segment indicator or course line
3 Vernier deviation indicator – an off-course "fly to" indicator
4 Aircraft heading
5 Command heading
6 Compass rose
7 Projection lamp brightness control
8 Projection lamp change
9 System annunciators
10 Selectable north-up or heading-up map orientation
11 Selectable readout of ground speed, ETE, or distance to go

The Hughes Moving Map Display is shown in Figure 12. The Hughes Aircraft Area Navigation System (moving map display) consists of panel-mounted map-type display for each pilot. The display presents an optically - projected moving map showing aircraft position by means of an aircraft symbol projected at the center of the display. Other guidance symbols are a Route Segment Indicator, Vernier Deviation Indicator, and a Command Heading Index. The various computer-driven symbols are projected in bright colors against a negative white-on-black chart of the area. Charts are stored within the unit on a strip of 35 millimeter microfilm containing 256 individually-selectable chart frames. Complete high altitude coverage for a domestic U.S. carrier is provided by 13 of the available 256 chart frames. Forty-six frames are required to provide complete low altitude coverage. Thus, 197 of the 256 frames remain for use in presenting terminal area charts, approach plates, check lists, emergency procedures, or any other type of graphic material desired for presentation to the crew.

FIGURE 13

CALIBRATED AIRSPEED INDICATOR

The calibrated airspeed indicator display is shown in Figure 13. Airspeed indicators are installed on both the captain's and the first officer's main instrument panels. The calibrated airspeed indicator has a dual redundant display. The airspeed is presented with a needle indicator on a peripheral scale and with a three-digit direct readout display. The maximum allowable airspeed is presented by a pointer of contrasting appearance against the peripheral scale. Speed command is presented by an index moving around the outer profile of the dial. Both the calibrated airspeed and the command speed track correctly when the electrical signal inputs are changing at rates equivalent to 600 knots per minute. The instrument sensitivity is less than 1.0 knot. The accuracy of the indicator is + 1 knot including hysteresis, resolution and friction effects. Four different scale factors exist in the instrument over a range of 60 to 650 knots.

The instrument non-linearity introduced by the four different scale factors can be programmed on the digital computer. Two input channels to the airspeed indicator are required if the scale factor are programmed on the computer. One channel is used for the linear digital readout display; the second channel is used for the needle indicator display. Two separate servo systems are required to operate the analog needle indicator and the digital display. Two additional servos are required to drive the maximum allowable airspeed and speed command indicators.

A resolution of one knot for the simulator calibrated airspeed indicator requires a 10-bit binary word input to the instrument. The slew rate of the airspeed indicator is 600 knots/min, equivalent to a shaft rate of 324 deg/min or .9 rev/min. The quasi closed loop direct digital drive system with a resolution of .25 deg/step is capable of 20.52 rpm. This capability exceeds the SST requirement by a factor of more than 20. The damping of the direct digital drive instrument is controlled in the digital computer and is not adjustable in the simulator.

FIGURE 14

ALTIMETER

The altimeter display is shown in Figure 14. Altimeters are installed on both the captain's and the first officer's main instrument panels. Altitude is displayed by a five digit direct readout in addition to a needle indicator and a peripheral scale. The needle indicator makes one revolution for each one thousand feet of altitude change. Reference level barometric pressure in inches of mercury or millibars is manually set and displayed on a dial in the instrument face. An amber light in the upper left corner of the instrument case illuminates to indicate airplane deviation from command or set altitude. The indicator is capable of tracking correctly when the electrical signal inputs are changing at rates equivalent to 20,000 feet per minute (20 rpm). The sensitivity of the altimeter is one foot. With a barometric pressure setting of 29.92 inches of mercury, the error of the indicator is less than + 5 feet over the range of -1000 to + 80,000 feet. This tolerance includes hysteresis, resolution and friction effects.

A one foot sensitivity for the altimeter requires a 17-bit digital binary word input to the instrument to simulate the accuracy required in the SST. The use of a 16-bit word in the instrument provides a sensitivity of 1.2 feet which is sufficient for an SST simulation. The quasi closed loop direct digital drive instrument is capable of 20.52 rpm at .25 deg. increments. This rate is compatible with the 20,000 feet/min. requirement (20 rpm).

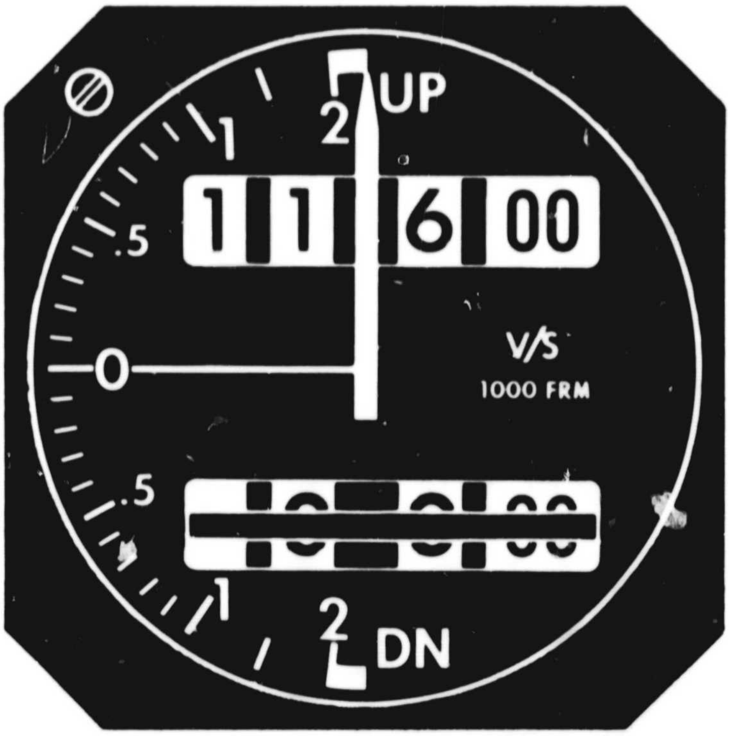


FIGURE 15

VERTICAL SPEED INDICATOR

The vertical speed indicator display is shown in Figure 15. Vertical speed indicators are installed on both the captain's and first officer's instrument panels. The vertical speed is presented on two five-digit readouts along with a needle indicator and a peripheral scale. Rate-of-climb is displayed on the upper digital readout and rate-of-sink is displayed on the lower digital readout. The digital display which is irrelevant to the flight condition is covered by a flag. The needle indicator sensitivity is + 10 feet per minute and the digital readout sensitivity is + 50 feet per minute. The instrument accuracy is +10 feet per minute including hysteresis, resolution and friction effects.

The difference between the digital readout sensitivity with a linear display and the needle indicator sensitivity with a nonlinear display can be controlled in the digital computer program. The vertical speed indicator will then require two input channels.

A sensitivity of 10 feet per minute vertical speed requires an 11-bit binary word input to the simulator instrument. The maximum slew rate of the quasi open-loop direct digital drive instrument with .25 degree incremental stops is 120 degrees per second. The required maximum slew rate for the vertical speed indicator is approximately 80 degrees per second with a maximum update rate of 20 per second.

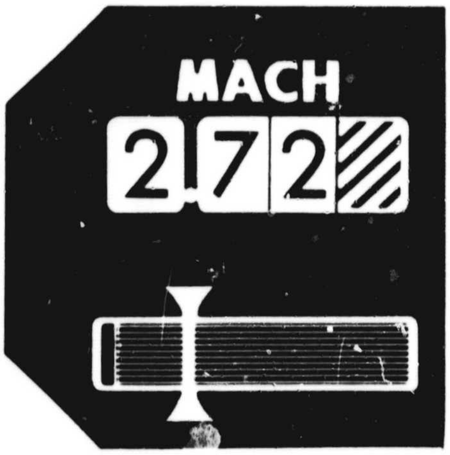


FIGURE 16

FIGURE 17

MACHMETER

The Machmeter display is shown in Figure 16. Machmeters are installed on both the captain's and first officer's instrument panels. Mach number is displayed by a three digit counter with two decimal resolution. The Mach number is also displayed pictorally by a tape moving horizontally against a fixed index. The tape is green during flight in the design Mach number range. As the maximum Mach number is approached and reached, the tape color changes from green to amber and then red. The Machmeter range is from 0.20 to 3.00. The meter sensitivity is .001 and is capable of tracking correctly when the electrical signal inputs are changing at rates equivalent to 1.0 Mach number per minute. The accuracy of the indicator is .001 Mach which includes hysteresis, resolution and friction effects.

A 12-bit binary word is required to give the simulator Machmeter a sensitivity of .001. Since the aircraft Machmeter is primarily a digital-display instrument, either an electromagnetic indicator or the actual aircraft Machmeter can be used for the simulator display. No provisions have been included to simulate the moving tape using direct digital drive. The maximum pdate rate on the Machmeter is 20 times per second.

ENGINE THRUST INDICATOR

The requirements for the engine thrust indicator are in the planning stage. An analog instrument with a three digit direct readout as shown in Figure 17 is being considered. Both positive and negative (reverse) thrust are provided on the needle indicator scale. One engine thrust indicator for each engine(total of 4) is installed in the central instrument panel. The engine thrust sensitivity is 100 lb. and is capable of tracking correctly when the signal inputs are changing equivalent to a rate of 10,000 lb. per second.

A sensitivity of 100 lb. requires a 10-bit binary word input. The slewing rate requirement of 10,000 lb. per second (30 degrees per second) is well within the capabilities of the direct digital drive system.

INTERFACING COCKPIT CONTROLS

The problem of interfacing the cockpit controls (control column, rudder and throttle) to the computer is closely related to the instrument interface problem. Consider as an example the pilot's longitudinal control column inputs.

The pilot's control column in the SST consists of two push rods which protrude from the instrument panel. These push rods move linearly in and out of the instrument panel to control the pitch attitude of the aircraft. The total system accuracy for the SST simulation of the control column should be at least 1/2 percent.

A conventional control column was used in the SST moving base simulation conducted at Norair. With the conventional control system, the pilot is allowed +6 1/2 inches of control column displacement on a 30 inch radius. The total column angular limit is 24.8 degrees. For a maximum error of 1/2 percent the shaft of the analog-to-digital converter system must maintain an overall system accuracy of .12 degrees (7.44 minutes) or .065 inches of column travel. A typical measured maximum pilot response for tracking rate consideration is 100 deg/sec. with an inoperative feel system.

Three Digital conversion methods are conventional analog-to-digital converters, encoders and synchro-to-digital converters. The existing analog-to-digital converter with sensing potentiometers of .025 percent linearity are used to provide a basis for comparison.

ANALOG-TO-DIGITAL CONVERTERS

The analog-to-digital converter with a 13 bit word contains a 2.6 minute error. The accuracy obtained from a single turn potentiometer of .025 percent linearity is 5.3 minutes which produce a minimum system error of 7.9 minutes or .693 per cent. These errors do not include power supply variations or wiper noise errors. The cost of the precision potentiometer is $400 per unit.

ENCODERS

Digital shaft encoders require at least 12 bit accuracy for a .5 percent minimum error. These units are direct shaft angle-to-digital converters. More than one revolution is required for 12 bits of information. The mechanical encoders require additional circuitry to ensure elimination of switching errors. The optical encoders are reliable but relatively expensive. Complete encoder units which provide the required resolution cost upwards of $1000. Solid state versions are more. Mechanical encoders with associated equipment which have 1 degree accuracy cost a minimum of $600.

TABLE 3
COCKPIT CONTROL INTERFACE COMPARISON

Devices	Advantages	Disadvantages	Remarks
Pots	Not temperature sensitive. Generally lower in cost.	Needs calibration. Accuracy changes with resistance-slider wear. Slider outputs are prone to produce noise. Accuracy dependent upon power supply ripple and balance.	Cost was from $350 - $600 for infinite resolution potentiometer in the .025% .015% linearity range. For accuracy involved loading must be a minimum.
Shift Encoder	Basic configuration is low cost. The most direct conversion method.	Requires additional equipment to reduce switching errors and eliminate age problems.	Price $700 - up for .1 degree accuracy. Units are generally multi-turn for 13 bit resolution. Optical encoders best but cost considerable more.
Synchor - Digital Converter	All solid state units need no calibration. Extremely long life. At least 14 bit resolution. Standard synchro inputs.	Relative moderate cost. Tend to have slow tracking rates.	Units must not load synchros for accuracy needed. For 360° tracking and 14 bit resolution Data Device Corp. appears to have optimum converter for accuracy required.
Synchros	Extremely long life. Simple to operate. Needs no calibration. High accuracy. No switching or drift problems.	Requires 400 Hz power. Errors increase with temperature extremes.	The optimum synchro units available appear to be Reeves Instruments 1 minute accuracy < $400.

SYNCHRO-TO-DIGITAL CONVERTERS

Synchro-to-digital conversion provides accurate, reliable data collection at a reasonable cost. The complete data collection system consists of a precision synchro or resolver with a linearity of 1 minute or better, and a solid state miniature module with 14 bit resolution of an accuracy of + 4 minutes + .5 least significant bits. Tracking rates of 360 deg./sec. and acceleration rates of 20 deg./sec. with full accuracy are available. The coding output is binary with the most significant bits representing 180 deg. The system can provide maximum reliability with a minimum of maintenance. The calculated overall system resolution and tracking response exceeds 1/2 percent and 100 deg./sec. respectively. Synchro-to-digital conversion systems which provide acceptable accuracies are available for less than $1000.

A comparison of the cockpit transducer methods is shown in Table 3.

SST DATA REQUIREMENTS

The Boeing Company has established on-line data recording requirements from an SST simulation which was conducted on the Norair moving base simulator at Hawthorne, California.

The on-line data obtained during this simulation experiment were used as final data. A 64-channel recording capability was necessary to record important variables from the sixteen degree-of-freedom simulation. A list of the types and number of variables recorded during this test is shown in Table 4. The maximum frequency of the SST simulation conducted at Norair was 5Hz. This frequency limitation was imposed by the frequency response limitation of the moving base and the amount of analog computer equipment available to solve the airframe equations of motion.

Eight analog plotters were used for the SST simulation at Norair. Each plotter had an eight-channel capability. The chart paper was 15 inches wide allowing 1-9/16 inches per channel for plotting each variable. The channel width was adequate for recording data. Each channel on the chart paper was divided into 50 divisions. Since the algebraic signs of the variables changed with time, 25 divisions were used to represent the maximum values of the variables. The pen trace width was approximately one-half a division. The resolution was one-half a division out of 25 or 2 percent. The analog plotter accuracy was sufficient for the Norair simulation tests.

A frequency capability of 10 Hz is desirable to investigate SST high frequency structural mode response. A frequency response of five to ten times the maximum frequency is desirable if phase distortion is to be minimized during impulse or step command inputs.

TABLE 4
VARIABLES RECORDED ON SST MOVING BASE SIMULATION

RECORDED VARIABLES	NO. VARIABLES
RIGID BODY PERTURBATIONS	14
PILOT INPUTS	4
STABILITY AUGMENTATION OUTPUTS	4
CONTROL SURFACE DEFLECTIONS	4
GUST DISTURBANCES	7
STRUCTURAL DISTURBANCES	10
MOVING BASE INPUT SIGNALS	10
ACTUAL MOVING BASE RESPONSE	6
TOTAL NO. VARIABLES	59

FIVE REDUNDANT VARIABLES WERE RECORDED FOR INPUT-OUTPUT COMPARISONS

DATA RECORDING SYSTEMS

The function of a plotting system is to provide a data analyst with computer output data in a pictorial or graphical form. Two basic types of plotters are available, direct digital plotters and analog plotters. A digital plotter or an analog plotter with digital to analog interface equipment can be used to plot digital data. Direct digital plotters, as compared to analog plotters, are drift-free and accuracy is not depended upon voltage stability. However direct digital plotters have numerous disadvantages. This part of the report describes data recording systems and their advantages and disadvantages as related to data recording requirements for SST simulations.

STEPPER MOTOR DIRECT DIGITAL PLOTTERS

CalComp is an example of stepper motor digital plotters. All CalComp incremental electromechanical ink-on-paper plotters operate on the same principle. Digital commands activate step motors to produce the graph or drawing. A separate motor controls the movement along each axis. Decoded input commands from the digital computer produce increments of pen movement in either direction along either axis, or at some angle relative to the axes. The size of the incremental unit of movement is determined by the gear ratio in the plotter.

The CalComp plotter does not have drift or inaccuracy problems due to voltage instability which is inherent in analog plotters. CalComp offers interface units for on-line plotting of digital data from most standard computers. The controllers for CalComp plotters incorporate operator convenience features and are compatible with the available digital plotters. CalComp on-line systems are capable of time-shared operations with other input/output equipment and, when equipped with core buffer storage, can accept high input data rates.

The CalComp 600 Series digital plotter has a maximum operating speed of 900 increments/sec. (1 increment = .00125 in.) and a speed rate up to 6.3 inches/sec. It also has remote and time-shared capabilities. Both 8-vector and 24-vector input command formats are compatible on the 600 Series.

A special Zip Mode operating Speed (equivalent to 1687 increments- per-second) with a speed rate up to 23.8 inches/sec. is available on the CalComp 700 Series.

CalComp equipment can produce drawings and plots with accuracy down to .005 inch, with repeatability and can retrace a plot or curve without discernible deviations. No system using analog conversion can achieve this degree of accuracy.

The CalComp plotter does not have multichannel capability. One plotter is required for each channel of data recorded. Sixty-four channels of data require 64 individual plotters. This redundancy is an important economic consideration and requires additonal computer overhead time for the plotter in a real time digital simulation.

The complex electromechanical mechanism which contains the pen carriage and the ball-point pen (or the optional liquid-ink pen) can have maintenance problems.

ELECTROSTATIC DIGITAL PLOTTERS

Of the vendors contacted for information on plotting equipment, only Varian offered an electrostatic plotter. The Varian Statos series of recorders combine electrostatic writing and digital logic circuitry, for high speed graphical printout of digital data. A unique feature of the Statos concept is the small number of moving parts; only the paper transport system has moving components. Statos 5 records various digital signals by means of a fixed recording head. Electrostatic charges are placed on the dielectrically-coated paper under the fixed styli when the individual styli are addressed. A digital logic switching scheme, programmed discretely or sequentially, is used to energize the styli array to permit extremely fast writing, unencumbered by mechanical motion. A permanent black or gray image is immediately formed on the electrostatically-charged areas as the paper passes through a toner in the recorder. No post-fixing or further processing of the paper is required.

The Statos 5 recording head consists of 1024 discrete styli, selectable for 8, 16, 32, or 64 styli per channel, for 128, 64, 32 or 16 channels, respectively, side-by-side writing. Paper speed is either synchronous (up to 4 inch/sec.) or asynchronous (.005 in./step up to 150 steps/sec.). The Varian Statos 5 plotter is capable of plotting up to 800,000 points/second when used as an on-line plotter. Since only 8 styli (1 styli/channel) are required to represent 8 distinct traces per scan, only eight 10-bit words are needed for addressing each step. The write time per point is 6 microseconds.

However, the maximum number of scans/second is limited to 200 scans/inch since the paper is stepped along in .005 inch discrete increments. For a synchronous paper speed of 4 in./sec. and a 10 Hz input the maximum scan rate is 800 scans/sec. or 80 scans/cycle. The resolution along the Y-axis is the resolution of the styli-head which is 80 styli/inch or 128 points/channel where each of the eight channels is 1.6 inches wide.

Since eight 10-bit binary words are needed for each scan and the maximum scan rate is 800 scans/sec., the required input bit rate is 64,000 bits/sec. for eight trace channels. This rate does not exceed the digital computer output capabilities. Figure 18 shows a representative sketch of one of the eight channels with attendant resolution along both the X-axis and Y-axis for a 10 Hz input. Some of the multi-channel capabilities of the electrostatic plotter are shown in Table 5.

TABLE 5
VARIAN STATOS 5 - MULTI-CHANNEL CAPABILITY

NO. OF CHANNELS	STYLI POINTS PER CHANNEL	CHANNEL WIDTH (INCHES)
1	1,024	12.8
2	512	6.4
4	256	3.2
8	128	1.6
16	64	.8
32	32	.4
64	16	.2
128	8	.1

An advantage of the Varian electrostatic plotter over the CalComp plotter is the simplicity of the printing assembly. A fixed recording head eliminates all moving parts and inertia in the writing system except for the paper transport mechanism. The Statos 5 prints its own chart grids and time bars. There are no time-scaling inaccuracies associated with paper adjustments. The plotter prints a fine, sharp line trace. The paper is insensitive to light, does not fade with time, and is easily reproducible. An example of an electrostatic graph is shown in Figure 19. Optional equipment is available to shade gray or fill in areas under the graph as illustrated in Figure 20.

The Statos 5 has multi-channel capability up to 128 channels. The multi-channel capability is an advantage over any single channel plotter as long as the attendant decrease in resolution is tolerable.

EIGHT CHANNEL ELECTROSTATIC PLOTTER OUTPUT FOR A 10Hz INPUT

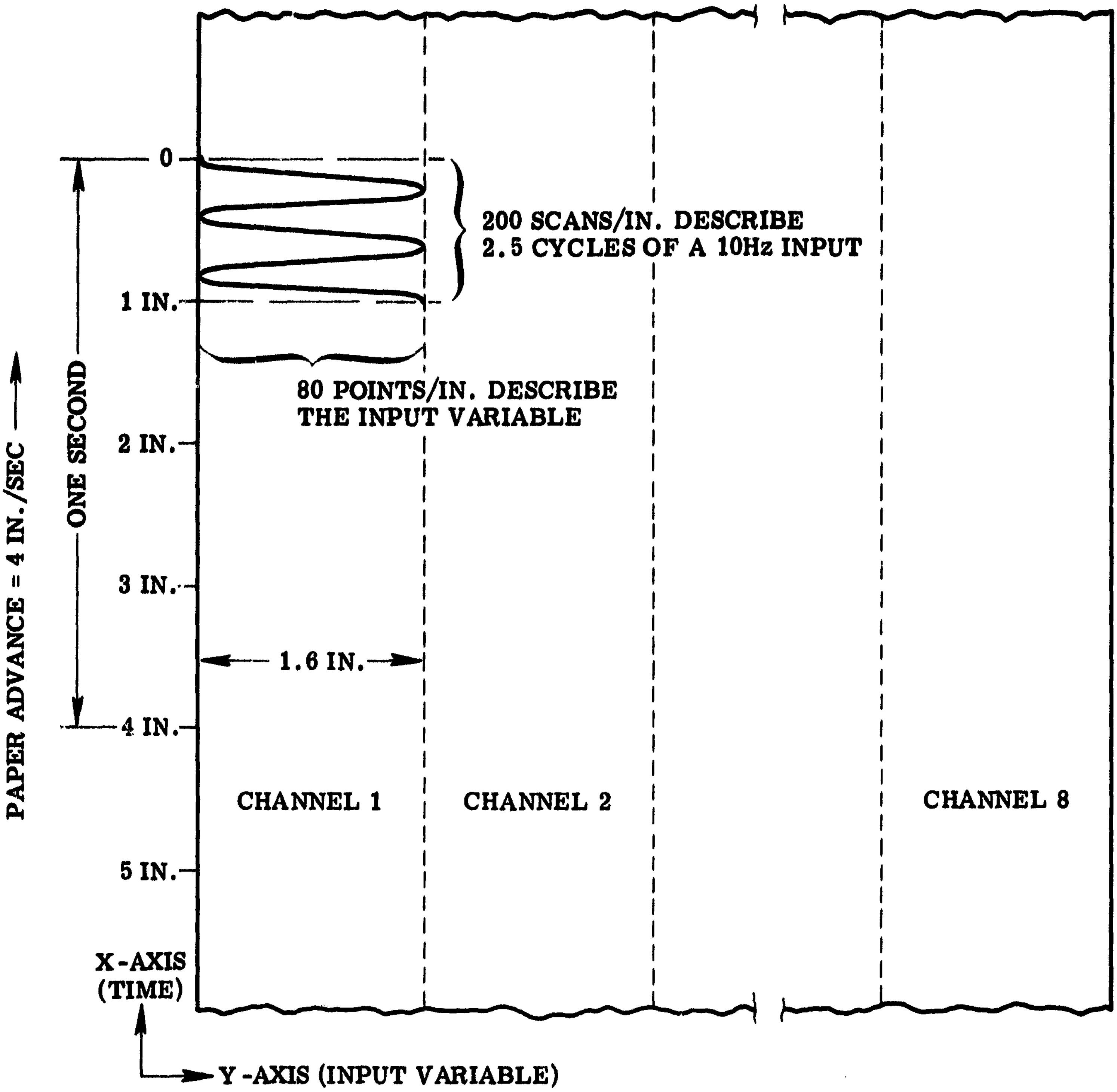
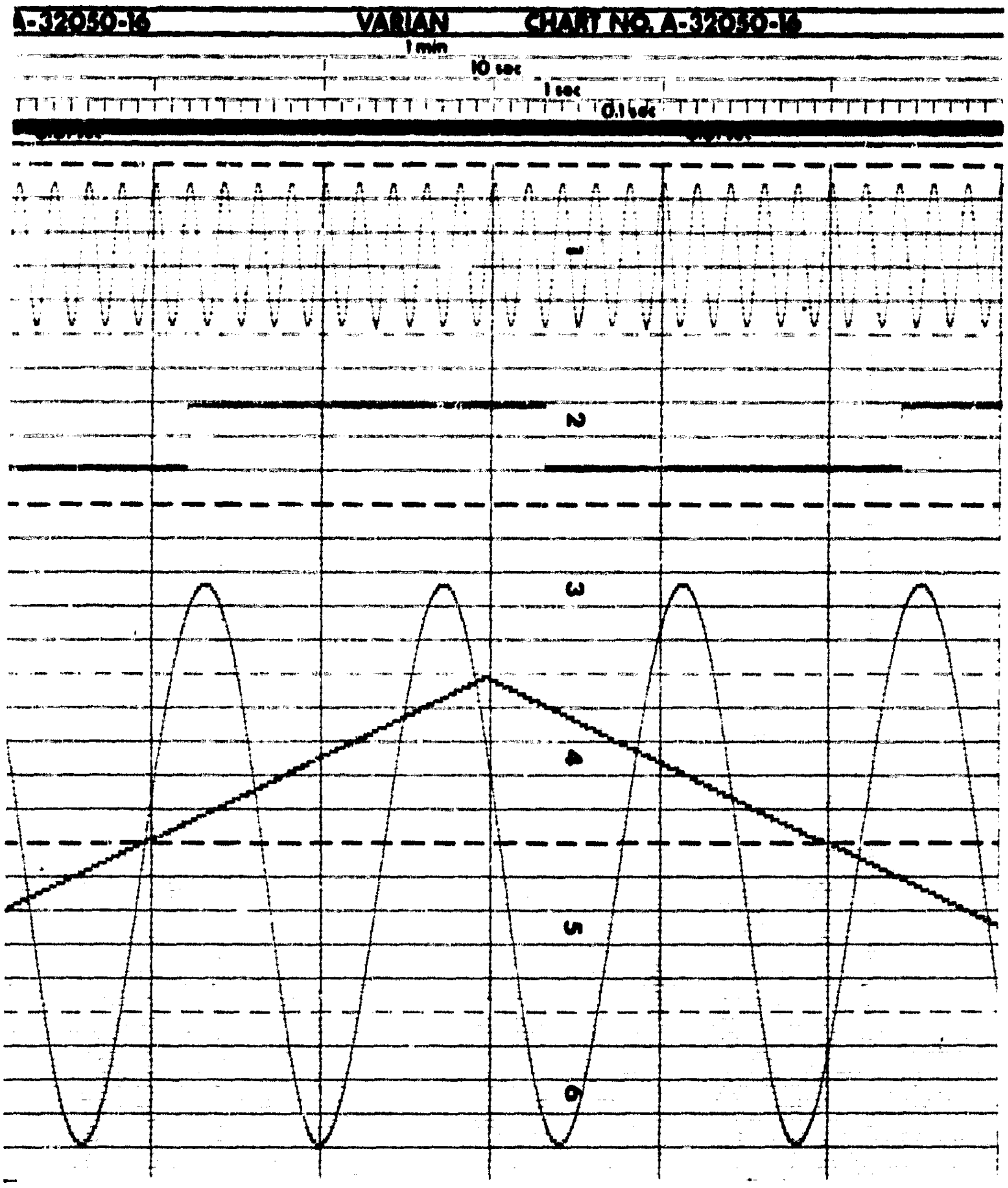


FIGURE 18



VARIAN ELECTROSTATIC GRAPH

FIGURE 19

VARIAN ELECTROSTATIC SHADED GRAPH

FIGURE 20

The digital information is used to discretely address the individual styli in the fixed recording head. Drift and voltage instability errors which occurs in analog plotting equipment are not present in the Varian electrostatic plotter.

Because the number of styli in the recording head are fixed, the graph resolution decreases as the number of data channels increase. For example if all 128 channels are used, a resolution of 8 points per channel is available for the Y-axis (1024 styli/128 channels = 8 pts/ch.). The resolution along the X-axis remains the same for any number of channels programmed.

The carbon particles, deposited on the paper, have a tendency to smear when the paper is handled.

The cost of the Varian Stator 5 electrostatic plotter is approximately $15,000. It is a suitable plotter for recording on-line SST simulation data.

ANALOG STRIP CHART RECORDERS

With appropriate interface equipment analog strip chart recorders can be used to plot digital computer output data. The advantages of analog strip chart recorders are:

1. Less frequent updates are required with low pass filtering to present a continuous record.
2. Many of the variables for which plots are desired are available at the direct digital drive controller or already in analog form. The computer time for updating of a digital plot is eliminated.
3. Scaling can be easily changed without computer reprogramming.
4. Existing analog recording equipment can be utilized providing analog and digital plots through digital-to-analog converters.

A program was written to determine the bit length requirements of the digital-to-analog converters necessary to obtain a satisfactory strip chart display of time varying digital data. The function

$$f(x) = \sin x + \sin \frac{x}{2}$$

was input to simulated digital-to-analog converters with bit lengths ranging from 2 to 13. The input to the converter was updated 50 times per cycle of maximum frequency, converted to analog voltage, and plotted on an EAI 8875 8-channel strip chart recorder. The strip chart data for bit lengths of 3, 6, 8 and 13 are shown in Figure 21. No more than 8 bit digital-to-analog converters are required to produce a relatively smooth unfiltered output. For on-line data monitoring purposes, a 5 or 6 bit converter would suffice with sufficient update rate and output filtering.

The cost of an EAI 8875 8-channel strip chart recorder is $12,800. Eight bit digital-to-analog converters without power supplies can be purchased for approximately $100 per converter.

DIGITAL DATA RECORDERS

If sixty-four variables are recorded for later data reduction and all recording is done digitally, the data storage requirements and transfer rates for variables with a 10 Hz maximum frequency content and 10 updates/cycle is 6400 updates/sec. or 2 million data points per five minute run.

This data recording requirement does not exceed the capabilities existing tape or disc storage units. Use of a digital computer with a direct memory access channel and automatic data channel processor requires little computer overhead per frame time for data recording.

In actuality some of the data will be in analog form. This data may be recorded on FM tape for later reduction relieving the storage requirement given above.

PROJECT ENGINEERS CONSOLE

The project engineer needs to be conversant in computer programming and aware of problems peculiar to digital simulations. His primary efforts need to be directed toward supervising tests, interpreting data, and making engineering decisions. The console is designed to aid the project engineer in the performance of his engineering tasks. The design of the project engineer's console should not compromise the capability of a simulator for use as a training facility or a developmental tool.

DIGITAL/ANALOG BIT REQUIREMENTS
50 UPDATES/CYCLE OF MAXIMUM FREQUENCY

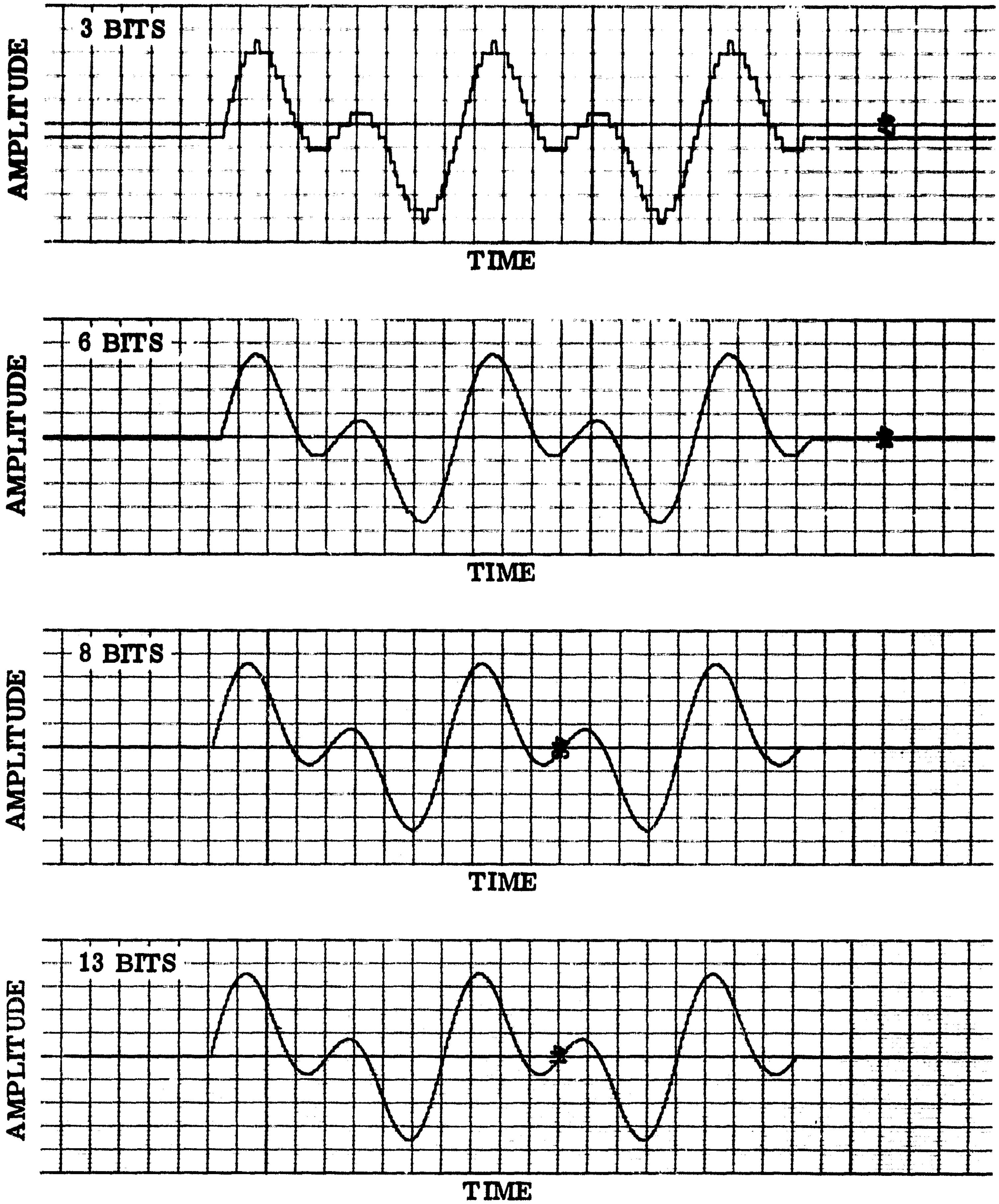


FIGURE 21

COMPONENTS AND OPERATING PROCEDURES

Engineers experienced in moving base simulator tests suggest the following components and operating procedure for the project engineer's console.

1. A side arm controller input device to allow flying the empty cab from the engineer's station. This feature will allow either the engineer or pilot to test fly a new configuration before actual on-board testing. Flight control can be transferred to the engineer's console from the cab only.

2. Two panel lights to indicate whether flight controls originate from the cockpit or the project engineer's console.

3. Six groups of thumbwheel switches to load four significant figure decimal numbers into the digital computer. The digital computer program will obtain values for pre-specified parameters from registers loaded by the thumbwheel switches. The values should be displayed in decimal form at the console. The register value to be displayed may be chosen by a six position switch.

4. A TV monitor to display the external visual cues seen by the pilot.

5. A TV picture of the pilot's instrument panel or a second set of basic flight instruments to provide flight information at the project engineer's console. The TV picture would be less expensive and the preferable option if sufficient resolution can be obtained and the camera positioned to give an unobstructed view of the instruments.

6. A strip Chart Recorder with no more than eight channels being displayed. The variables displayed on this strip chart recorder should be critical variables which would allow the project engineer to determine if the simulation is proceeding correctly. The remainder of the data collection should be done in the computer area.

7. A decimal display of the digital variables being displayed on the strip chart recorder to allow an accurate check of variable values in hold or IC modes. The variable displayed should be selectable by a switch at the console.

8. A Y-Z plotter to allow the project engineer to monitor the lateral and vertical motion and position of the cab.

9. An interlock mode control system to allow starting the experiment by the computer operator, the project engineer, or the pilot. The experiment could be started only when the computer operator, moving base system operator, project engineer, and pilot have put their respective switches in the "ready" position. A red and green light system would be available at these stations indicating the status of the other stations ("ready" - "not ready"). The project engineer, computer operator, moving base systems operator and the pilot would each have the capability to put the computer in "hold" as desired.

10. Three panel lights to indicate "initial condition", "operate", and "hold" modes.

11. A two channel audio recorder to record pilot and project engineer comments.

12. A communications panel to route all conversation with the crew through the engineer's console. The isolation of the crew from unnecessary conversation by the simulator operators avoids biasing the crews. The circuitry should be independent of the conventional facilities required for the simulation of airplane communication facilities. An audio call tone through the telephone receiver at the Test Conductor's station and a blinking light at the flight crew's stations will provide for signaling between stations. This system should be completely independent of normal simulator power.

13. A clock

14. A "time in operate" clock. This clock should go to hold when the simulator is placed in the hold mode.

15. Necessary switches to control the functions described above.

The relationship of the project engineer's console to the total simulator is shown in Figure 22. A pictorial representation of the proposed console is shown in Figure 23.

LINKAGE FOR PROJECT ENGINEER'S CONSOLE

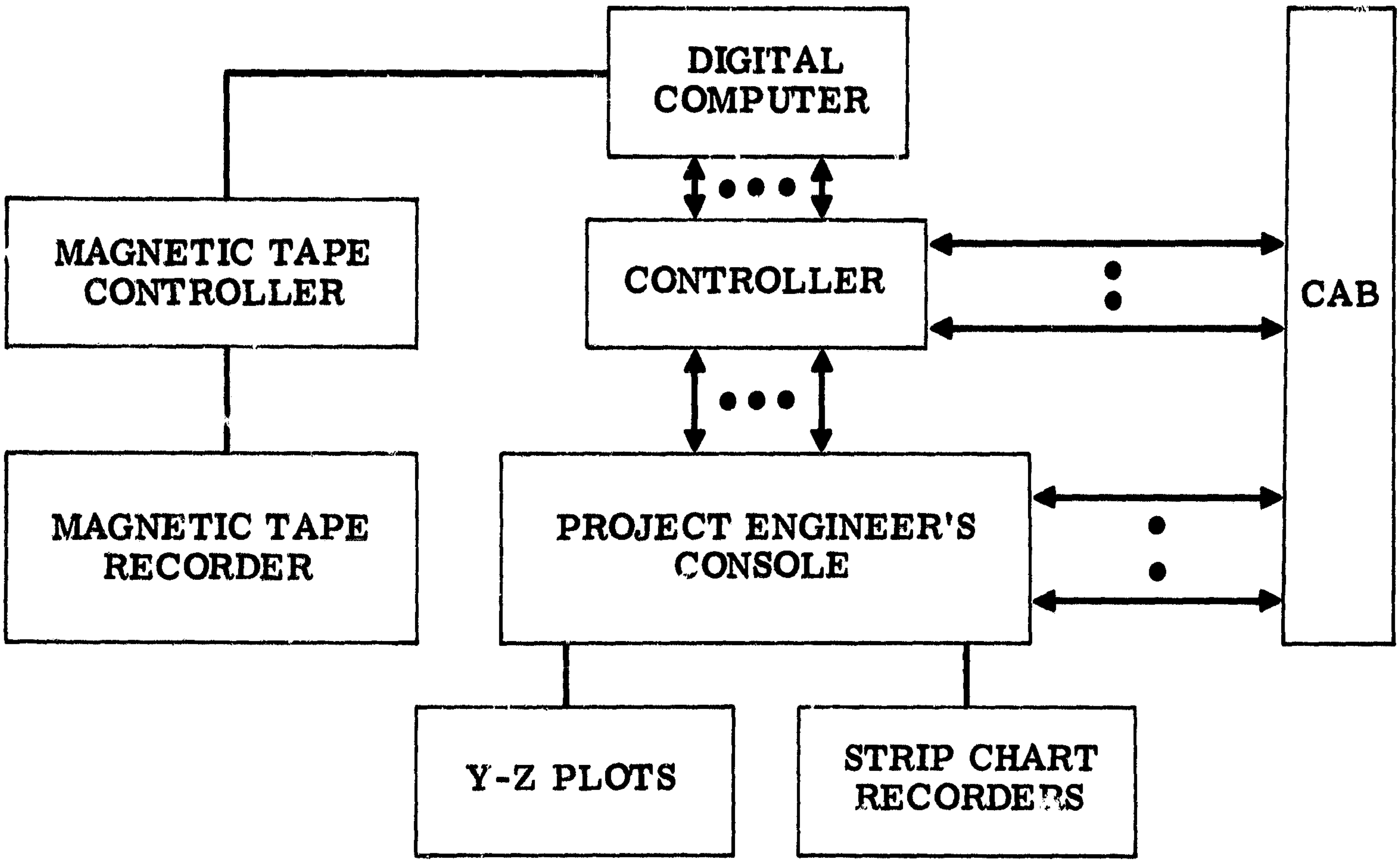


FIGURE 22

COMPUTER LINK

No additional controller is required for connecting the project engineer's console to the digital computer. The direct digital drive controller is a sufficient link to the console since it consists of addressable registers and any digital device with proper logic levels and bit requirements can be attached to the controller. The number of lines required to connect the engineer's console to the controller can be greatly decreased with a slight increase in programming complexity and Central Processing Unit time. One register in the controller can be used as an address register for information transfer to the engineer's console and another register in the controller can hold the information to be transferred. Address decode circuitry must be included in the engineering console to gate the data to the proper register or display.

PROPOSED PROJECT ENGINEER'S CONSOLE

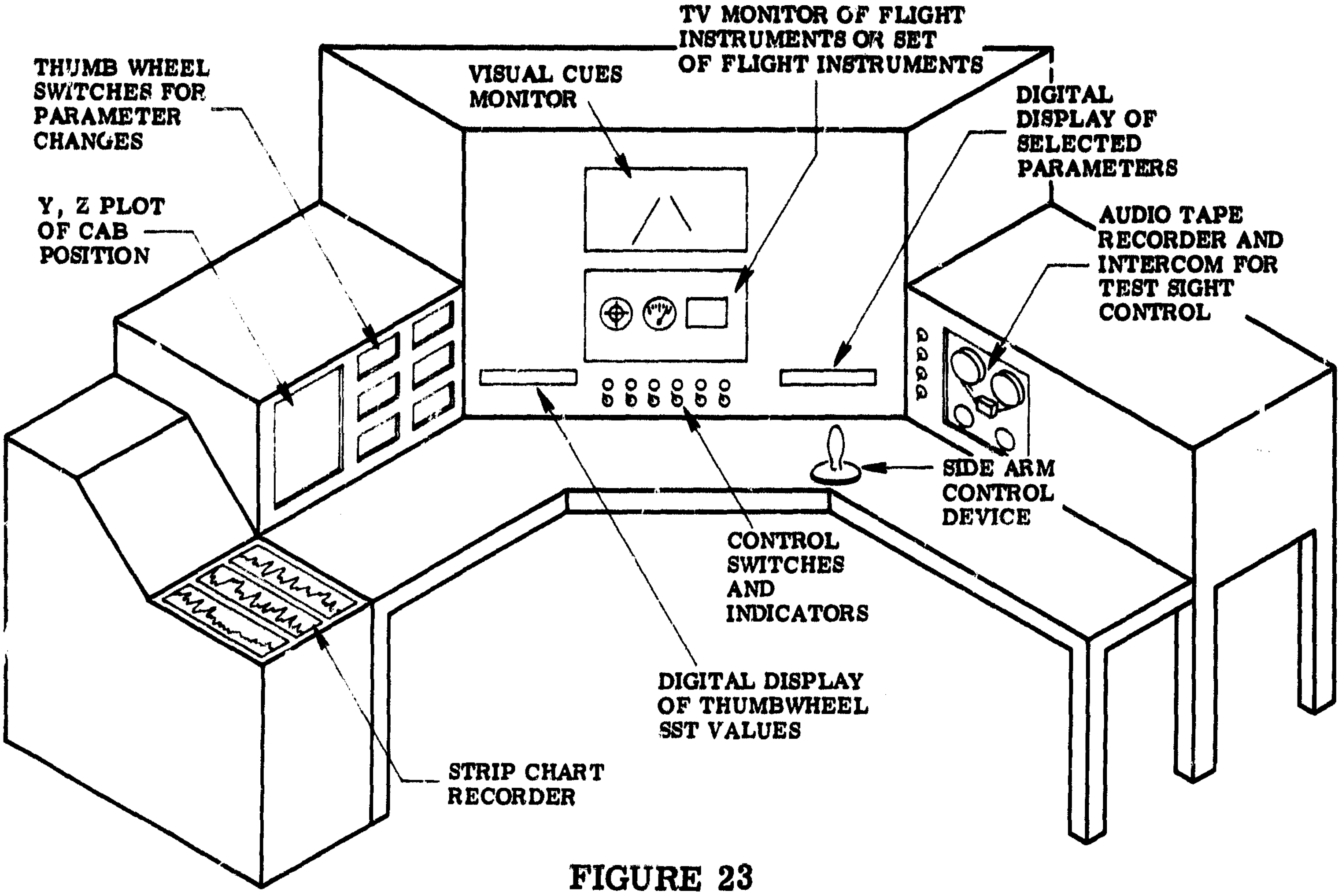


FIGURE 23

The devices that input data to and received data from the project engineer's console are shown in the simplified block diagram of Figure 22.

CONCLUSIONS

The quasi closed-loop direct digital drive instrument developed by the Boeing Company Seattle possesses sufficient speed and accuracy to exceed the SST flight instrument specifications if updated at the required 20 times per second.

Further development of the closed-loop incremental feedback direct digital drive system is required before this method could be used in a SST simulation.

Direct digital drive is feasible for operating some but not all flight instruments in an SST simulation. Integrated direct digital drive units are not commercially available; however, equipment components are available to construct direct digital drive systems. Closed-loop or quasi closed-loop direct digital drive systems in SST simulations can:

1. Position simulator instrument indicators more accurately than the aircraft instrument indicator requirements.
2. Drive the simulator instruements at rates surpassing the aircraft instrument rate requirements.
3. Simplify the link between the simulator cockpit and the computer.

4. Provide system operating diagnostic capability.

The calibrated airspeed indicator, altimeter, vertical speed indicator, Machmeter, and engine thrust indicator can be controlled with direct digital drive. Table 6 outlines the SST instrument specifications, and direct digital drive instrument capabilities. The direct digital drive instrument with .25 degree incremental steps can meet or exceed slewing speed requirements of all the instruments shown. The altimeter and engine thrust indicators each require only one electromechanical drive system with a gear system to display their associated parameters. The calibrated airspeed indicator and vertical speed indicators both require two electromechanical drive systems because of the nonlinear displays. An electromagnetic indicator or the actual aircraft Machmeter can be used for the simulator Machmeter, since it is primarily a digital display instrument. Update rates, operational range, and digital requirements for the SST air data instruments are shown in Table 7

TABLE 7
SST AIR DATA COMPUTER PARAMETERS

PARAMETER	AIR DATA COMPUTER OPERATIONAL RANGE	UPDATE RATE PER SEC	BINARY OUTPUT			BCD OUTPUTS	
			BINARY WORD RANGE	SIGNIFICANT BITS	RESOLUTIONS AND UNITS	SIGNIFICANT FIGURES	LEAST SIGNIFICANT FIGURE
CORRECTED ALTITUDE	-1000 TO +80,000 FEET	20	±131,071	17	1.0 FOOT	5	1.0 FOOT
VERTICAL SPEED	±20,000 FT/MIN	20	±20,470	11	10 FT/MIN	4	10 FT/MIN
COMPUTED AIRSPEED	60 TO 800 KNOTS	20	±1023.75	12	0.25 KNOT	3	1.0 KNOT
MACH	0.2 TO 3.0 MACH	20	±4.0955	13	0.0005 MACH	4	0.001 MACH

The EADI, the HSI, and the moving map display require both analog and hybrid inputs. Conventional conversion equipment and associated interfacing is necessary for the digital computer to control these flight instruments. Future improvements in digital equipment could make an all digital drive system feasible for an SST simulator.

Analog strip chart recorders with 8 bit digital-to-analog converters are sufficiently accurate for plotting on-line SST simulation data.

The project engineer's console should have as many of the features listed in this report as economically feasible.

A 16 degree-of-freedom modal model may exceed digital computer frame time requirements. If so, hybrid computation must be used to satisfy the frequency requirements. Additional analog-to-digital and digital-to-analog conversion equipment must be available if direct digital drive instruments are used with hybrid computations.

TABLE 6
SST INSTRUMENT SPECIFICATIONS
AND
DDD INSTRUMENT CAPABILITIES

INSTRUMENT	CALIBRATED AIRSPEED		ALTIMETER		VERTICAL SPEED		MACHMETER		ENGINE THRUST	
SPECIFICATION AND CAPABILITY	SST	DDD	SST	DDD	SST	DDD	SST	DDD	SST	DDD
INSTRUMENT TYPE	POSITION FEEDBACK	STEPPER MOTOR	POSITION FEEDBACK	STEPPER MOTOR	POSITION FEEDBACK	STEPPER MOTOR	POSITION FEEDBACK	STEPPER MOTOR	ANALOG	STEPPER MOTOR
MAXIMUM INSTRUMENT SHAFT RATE (DEG./SEC)	54	120	120	120	NOT AVAILABLE	120	NOT APPLICABLE	120	30	120
MAXIMUM INSTRUMENT DISPLAY RATE	600 KNOTS/MIN.	32,000 KNOTS/MIN.	20,000 FT/MIN	20,000 FT/MIN.	NOT AVAILABLE	NOT APPLICABLE	1.0 MACH/MIN	100 MACH/MIN	10,000 LB/SEC	40,000 LB/SEC
DIGITAL DISPLAY	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
NEEDLE INDICATOR DISPLAY	YES	OPTIONAL	YES	OPTINAL	YES	OPTIONAL	NO	OPTIONAL	YES	OPTIONAL
DAMPING RATIO	.6→1.0	PROGRAMABLE	.6→1.0	PROGRAMABLE	.6→1.0	PROGRAMABLE	.6→1.0	PROGRAMABLE	.6→1.0	PROGRAMABLE
ACCURACY	± 1 KNOT	<± 1 KNOT	± 5 FT	<± 5 FT	± 10 FT/MIN	<±10 FT/MIN	± .001	<± .001	± 100 LB	<± 100 LB
RESOLUTION	1 KNOT	.25 DEG	1 FT	.25 DEG	10 FT/MIN	.25 DEG	.001	.25 DEG	100 LB	.25 DEG
BIT ACCURACY	12-BIT	10-BIT	17-BIT	16-BIT	11-BIT	11-BIT	13-BIT	12-BIT	NOT APPLICABLE	10-BIT
SCALES	LINEAR AND NONLINEAR	LINEAR AND NONLINEAR	LINEAR	LINEAR AND NONLINEAR	LINEAR AND NONLINEAR	LINEAR AND NONLINEAR	LINEAR	LINEAR AND NONLINEAR	LINEAR	LINEAR AND NONLINEAR

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10. Boeing Document No. D6A10109-1: Flight Deck Subsystem Specification.
11. Boeing Document No. D6A11301-1 TN:SST Flight Simulator Programming Specifications For the EAI 8400 Computing System.
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13. Hughes Aircraft Company: Navigation Director-System Description and Operating Guide, Report No. TM-902D, Culver City, California, November 1968.
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21. Control Engineering: Servo-Style Circuit Speeds Synchro-to-Digital Conversion, January 1968, pp. 65-67.
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23. The Electronic Engineer: A Building Block Approach to Digital-to-Analog Converters, May 1968, pp. 58-64.

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25. Astronautics and Aeronautics: The Simulator to Match the Transports to Come, September 1969, pp. 54-60.

26. Electronic Design: Multiplexing Slices Tons of Weight From Aircraft, October 24, 1968, pp. 25-28.

References 1 through 5 were utilized in the "Direct Digital Drive Concepts" section. References 6 through 14 were used in the section "Direct Digital Drive for SST Simulator Instruments." References 15 through 24 were used for the section "Interfacing Cockpit Controls." References 25 and 26 were general references.

APPENDIX A - STEPPER MOTOR PERFORMANCE

The stepper motor provides a preferred flux path configuration for the motor to align itself to the stator. There are several such configurations in a single rotation due to the form of construction and the need to economize on drives. Smaller stepping angles are also required. As an example, a given motor with 4 windings and 24 steps per rotation (15 steps) has 6 different positions for each step.

The Boeing Company made an evaluation of stepper motors operating at various speeds to meet instrument update rates. No commercially available stepper motor met its specification on reversing speed.

Several manufacturers' products were tested. Some manufacturers conducted tests in their own laboratories. Boeing conducted extensive evaluations on I.M.C., Cedar and Kearfott products. All three manufacturers failed to meet their specified reversing speed, without loss of step position. The stepper motors tested were required to reverse without losing any steps on the cycle of rotation. The test motors were controlled to run seven steps clockwise and then counter clockwise. The command speed was varied and the motor speed and output position was observed. The Kearfott motor gave the best performance. This motor met 70 percent of its rated performance and was selected to drive the instruments for the SST simulation. The Boeing Company rates the motor at 500 steps per second with 10 percent reduction in driving voltage.

APPENDIX B - EADI INSTRUMENT INFORMATION

The Electronic Attitude Director Indicator receives its signals from a television camera, radio altimeter, AFCS, INS, and VHF Navigation as follows:

Input	Signal Type	Scale Factor
Pitch Attitude	Synchro	1 / pitch
Roll Attitude	Synchro	1 / roll
Attitude Reference Valid Signal	28 Volts DC	On-Valid-Grounded-Invalid
Pitch Command (3-channels)	DC Voltage	+1.3 volts full scale
Bank Command (3-channels)	DC Voltage	+1.3 volts full scale
Command Data Valid Signal (3 channels)	28 volts DC	On-Valid Grounded-Invalid
AFCS Land Mode Selection	Switch Contact	Open/closed (closed with Land Mode Selected)
Speed Error	DC Voltage	+2.2 volts/full scale
Speed Error Data Valid Signal	28 volts DC	On-Valid Grounded-Invalid
Localizer Deviation	DC Voltage	+0.050 volts/full scale
Localizer Data Valid Signal	28 Volts DC	On-Valid Grounded-Invalid

Input	Signal Type	Scale Factor
Localizer Data Valid Signal	23 Volts DC	On-Valid Grounded-Invalid
Glide slope Deviation	DC Voltage	+0.150 volts/full scale
Glide slope Deviation Valid Signal	28 Volts DC	On-Valid Grounded-Invalid
Radio Altitude	DC Voltage	
Radio Altitude Valid Signal	28 Volts DC	On-Valid Grounded-Invalid
Attitude Comparison-Pitch	To be determined	1 / pitch
Attitude Comparison-Roll	To be determined	1 / roll
Flight Path Acceleration	DC Voltage	5 volts/0.50g
Flight Path Acceleration Valid Signal	28 Volts DC	On-Valid Grounded-Invalid
Flight Path	DC Voltage	0.2 volt/degree
Flight Path Valid Signal	28 Volts DC	On-Valid Grounded-Invalid
Drift Angle	Synchro	1 / drift angle
Flare Command	28 Volts DC	On-Valid Grounded-Invalid
Composite Video with Sync Negative	AC Voltage	1.5 volts Sync Negative Peak-to-peak
Control Panel Light Dimming	Variable 5 Volt AC	---------
Synchro Reference	26 Volts AC	---------

APPENDIX C - VENDOR AND SPECIALISTS CONTACTED

The following vendors and specialist outside the Boeing Company were contacted during the course of the contract for information regarding direct digital equipment and technology.

Vendor and/or Specialist	Equipment
Astrosystems 6 Nevada Drive New Hyde Park, New York 11040	D-S and S-D Converters
GAP Instrument Westbury, New York	D-S and S-D Converters
Northern Precision Laboratories, Inc. 202 Fairfield Road Fairfield, New Jersey 07006	D-S and S-D Converters Shaft Encoder
Airflyte Electronics Company 535 Avenue A Bayonne, New Jersey	Shaft Encoders
Transmagnetics, Inc. 134-25 Northern Blvd. Flushing, New York 11354	D-S and S-D Converters
Natel Engineering Company, Inc. 7129 Gerald Avenue Van Nuys, California 91406	S-D Converters
North Atlantic 200 Terminal Drive Plainview, New York 11803	D-A and A-D Converters D-S and S-D Converters
Datex Division 1600 South Mountain Avenue Duarte, California	Shaft Encoders
Ditran Division of Clifton Litton Industries 25 Adams Street Burlington, Massachusetts	D-A and A-D Converters D-S and S-D Converters
Teledyne Systems Company 200 North Aviation Blvd. El Segundo, California	D-S and S-D Converters
Data Technology, Inc. 65 Grove Street Watertown, Massachusetts	Shaft Encoders
Servo Corporation of America 111 New South Road Hicksville, New York	D-S and S-D Converters

Vendor and/or Specialist	Equipment
Singer Company, Instrument Division 3211 South LaCienega Blvd. Los Angeles, California 90016	D-A and A-D Converters S-D Converters
Vernitron 50 Gazza Blvd. Farmingdale, New York	D-S and S-D Converters Shaft Encoders
Weston Instrument, Inc. Transicoil Division Worcester, Pennsylvania	D-S and S-D Converters
Bendix Corporation Navigation and Control Division Teterboro, New Jersey	D-S and S-D Converters
Fairchild Space & Defense Systems 300 Robbins Lane Syosset, New York	D-A and A-D Converters Data Systems
Reeves Instrument Division East Gate Blvd. Garden City, New York 11530	Resolvers
AD Data Systems, Inc. 830 Linden Avenue Rochester, New York	D-A and A-D Converters
Litton Industries 20745 Nordhoff Street Chatsworth, California 91311	Shaft Encoders
Librascope Products Singer - General Precision, Inc. 808 Western Avenue Glendale, California 91201	Shaft Encoders
Disk Instruments, Inc. 2701 South Halladay Street Santa Ana, California 92705	Shaft Encoders
Collins Radio Company Cedar Rapids, Iowa 52406	SST Instrumentation
Kearfott Products Division Clifton, New Jersey	D-A and A-D Converters Stepper Motors Shaft Encoders

Vendor and/or Specialist	Equipment
Simmonds Precision Products Carlson Building Bellevue, Washington	SST Instrumentation DDD
Lear Siegler, Inc. Instrument Divion 4141 Eastern Avenue, S.E. Grand Rapids, Michigan	SST Instrumentation
Kollsman Instruments 80-08 45th Avenue Elmhurst, New York 11373	SST Instrumentation
Weston Instruments Weston - Newark Division 614 Frelinghuysen Avenue Newark, New Jersey	SST Instrumentation
Thomas A. Edison Instrument Division (Formerly Sunbeam Electronics) Division of McGraw-Edison Company 1400 N. W. 50th Street (Commercial Blvd.) Ft. Lauderdale, Florida 33307	SST Instrumentation
Hughes Aircraft Company Culver City, California	Moving Map Display
Astronautics Corporation of America Milwaukee, Wisconsin	Moving Map Display
Varian Associates Graphics and Data Systems Division 611 Hansen Way Palo Alto, Califonria 94303	Electrostatic Digital Plotter
Hewlett-Packard Company 1501 Page Mill Road Palo Alto, California	Digital Plotters
Honeywell, Inc. Industrial Division 1100 Virginia Drive Ft. Washington, Pennsylvania	Digital Plotters
California Computer Products, Inc. 305 North Muller Street Anaheim, California 92803	Digital Plotters
Conductron Corporation St. Charles, Missouri	DDD

Vendor and/or Specialist	Equipment
Muirhead Instruments Ontario, Canada	Stepper Motors DDD
General Electric Company Special Products - Research Binghamton, New York	DDD Indirect D-A Converters
Computer Industries, Inc. Graphic Systems Division 14761 Califa Street Van Nuys, California 91401	Digital Plotters
Clifton Division of Litton Industries Clifton Heights, Pennsylvania 19018	Stepper Motors Synchros
Dynalex, Inc. 885 Front Street Burbank, California 91502	A-D Converters
Baldwin Electronics, Inc. 1101 McAlmont Street Little Rock, Arkansas 72203	Shaft Encoders
Towson Laboratories, Inc. 3500 Parkdale Avenue Baltimore, Maryland 21211	S-D Converters
Bendix Flight & Engine Instruments Division South Montrose, Pennsylvania	Synchros
Computer Instruments Corporation 92 Madison Avenue Hempstead, New York 11550	Pots
Perkin-Elmer Corporation Electronic Products Division 131 Danbury Road Wilton, Connecticut 06897	Pots
New England Instrument Company Kendall Lane Natick, Massachusetts	Pots
Beckman Instruments, Inc. Helipot Division 2500 Harbor Boulevard	Pots

Vendor and/ or Specialist	Equipment
Data Device Corporation 100 Tee Street Hicksville, New York 11801	S-D Converters
Adage, Inc. 1079 Commonwealth Sbrnue Boston, Massachusetts 02215	A-D and D-A Converters
Electronic Associates, Inc. 185 Monmouth Parkway West Longbranch, New Jersey 07764	Digital and Analog Computers
Canadian Avionics Electronics Montreal, Quebec	DDD
Electrodevelopment Corporation Linwood, Washington	DDD
Burr Brown Research Tucson, Arizona	Digital Devices
Dr. G. Korn, University of Arizona Tucson, Arizona	DDD
Mark Connelly M.I.T. Cambridge, Massachusetts	DDD