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RESEARCHER'S GUIDE TO THE NASA AMES FLIGHT SIMULATOR FOR ADVANCED AIRCRAFT (FSAA)

John B. Sinacori, Robert L. Stapleford, Wayne F. Jewell, and John M. Lehman

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16. Abstract

The NASA/Ames Research Center Flight Simulator for Advanced Aircraft (FSAA) is described in terms useful to the researcher who intends to use it. Its performance, limitations, supporting software, and current checkout and operating procedures are presented together with suggestions to help the researcher prepare the experimental plan. The document addresses the FSAA's central computer, cockpit, and visual and motion systems individually but also relates their interaction. Data required, available options, user responsibilities, and occupancy procedures are given in a form that hopefully will facilitate the initial communication required with the NASA operations' group.

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LIST OF ABBREVIATIONS

ADC   Analog-to-Digital Converter

BPI   Bits Per Inch

BPM/BTM   Batch Process Monitor/Batch Timesharing Monitor

c.g.   Center of gravity

CP   Center Position

CPU   Central Processing Unit

CRT   Cathode Ray Tube

DAC   Digital-to-Analog Converter

DI   Discrete Inputs

DO   Discrete Outputs

EAI   Electronic Associates Inc.

EPR   Engine Pressure Ratio

FSAA   Flight Simulator for Advanced Aircraft

HSI   Horizontal Situation Indicator

HUD   Head-Up Display

IC   Initial Condition

I/O   Input/Output

IVSI   Instantaneous Vertical Speed Indicator

MOTHER   Monitor Time Handling Executive Routine

NASA   National Aeronautics and Space Administration

RAD   Rapid Access Device

RMS   Root Mean Square

RPM	Revolutions per Minute
SAFE	Six Axes Frequency Evaluation
SAS	Stability Augmentation System
STOL	Short Takeoff and Landing
USAF	United States Air Force
VFA	Visual Flight Attachment
wrt	With respect to

SECTION 1

INTRODUCTION

1.1 PURPOSE

This is a researcher's guide to the NASA Ames Research Center Flight
Simulator for Advanced Aircraft (FSAA). The primary objective of this
document is to provide a researcher with all the information about the FSAA
he needs to conduct a productive, efficient flight simulation experiment.
It is mainly a collection of data on the various elements of the system,
both hardware and software. It is user-oriented. Only that information
deemed at all useful to the researcher has been included. Its intent is
also to serve as a vehicle of communication between the researcher and the
simulation support groups. Care has been exercised in the use of language
common to both yet emphasizing the researcher's needs.

The FSAA is a complex aeronautical simulation tool that embodies
advanced concepts and performance addressed to present and future research
needs. It is supported by groups of NASA and contractor people that have
wide and diverse experience in the use of the equipment. Communication
between the researcher and these people is essential to a successful simu-
lation effort and this document seeks to aid that process.

While the simulation operations personnel thoroughly understand the
FSAA, the knowledge of the research objectives of each test comes from the
researcher. The operations staff should know at least the general test
objectives but it is generally impractical for the researcher to communicate
all the various facets and fine details of his program. Therefore, the
burden is on the researcher to provide adequate information to the operations
personnel. The more the researcher knows about the FSAA, the better he will
be able to supply this information and the better he will be able to take
full advantage of the capabilities of the FSAA.

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1.2 OUTLINE

Besides these introductory paragraphs, the guide is divided into five more sections, each addressing major subsystem components of the facility. Section 2 describes the software and hardware aspects of the central computational system including data acquisition and program control.

Section 3 gives details of the cockpit which includes the instruments, control loaders, head-up display, and sound generator.

Section 4 is a treatise on the outside visual display subsystem that describes the visual system concept, its performance, and related computational systems that drive it from information in the central computer. Existing and suggested checkout procedures are also outlined.

Section 5 describes the motion system. Data on its performance characteristics are provided. A major portion of this section describes the drive logic and its effects on the motion cues which will be provided to the pilot.

The last section, 6, contains a collection of procedures and suggestions that hopefully will assist in making the researcher's experience with the FSAA a productive one. It also contains an extensive data exchange list that should form the basis for initial communication with the NASA operations groups.

1.3 DATA SOURCES AND FORMAT

This document was prepared by a user/researcher group including people who have been in the roles of researcher, simulator support engineer, and simulator hardware designer. The data were obtained from the many people within the NASA structure that have contributed to simulation technology and specifically to the FSAA development. In some instances tests of the hardware were required to clarify performance or formulate descriptions. The data represent the most current properties of the FSAA and are updated every three months or whenever component modifications are implemented.

The data are by no means complete or representative of all the tests performed on the FSAA, but certainly reflect the aspects of the device that are important to the researcher. If portions of the guide appear irrelevant, it is because an attempt was made to ensure comprehensiveness.

The formats of the data are the ones commonly used by engineers working in the aeronautical disciplines. The use of symbols has been minimized and wherever possible standard nomenclature has been adopted. The guide is bound in a loose-leaf binder for use in the laboratory where additions, corrections, or modifications may be easily implemented. The writers encourage each user and members of the simulation support groups to revise, critique, and add to this document when necessary by submitting changes to the Simulation Sciences Division. Users are particularly urged to add comments and experiential data to the guide following the completion of their programs. This may be a powerful way of transforming the simulation "art" into science.

1.4 FSAA GENERAL DESCRIPTION

The FSAA is a general-purpose aircraft simulator that was designed to meet present and future transport aircraft research needs. Its advanced concepts and performance make it useful for a wide variety of simulation test purposes and its design includes high flexibility within an experimental laboratory.

Within one building, a large area houses a six-degree-of-freedom electromechanical motion system supporting a transport cockpit structure containing seats, instrument panels, flight controls, visual display hardware, and aural equipment. Adjacent to the main area is the control room which houses the operator stations, an entrance platform, and a visitor's observation platform. Below the operator's room is an array of electronic consoles and power units that provide drive power for the device. In an adjacent room, a central computing facility comprising many digital and analog computers and support equipment is maintained. In a nearby area,

two large terrain boards are mounted vertically with supporting light banks, gantry, and television equipment that forms the outside scene generation subsystem. A series of cables tie all this equipment together and to the central computing room where a computer control station is maintained and from where the researcher directs the simulation effort.

A photograph of the simulator area containing the motion system and cockpit is shown in Figure 1.4-1.

.
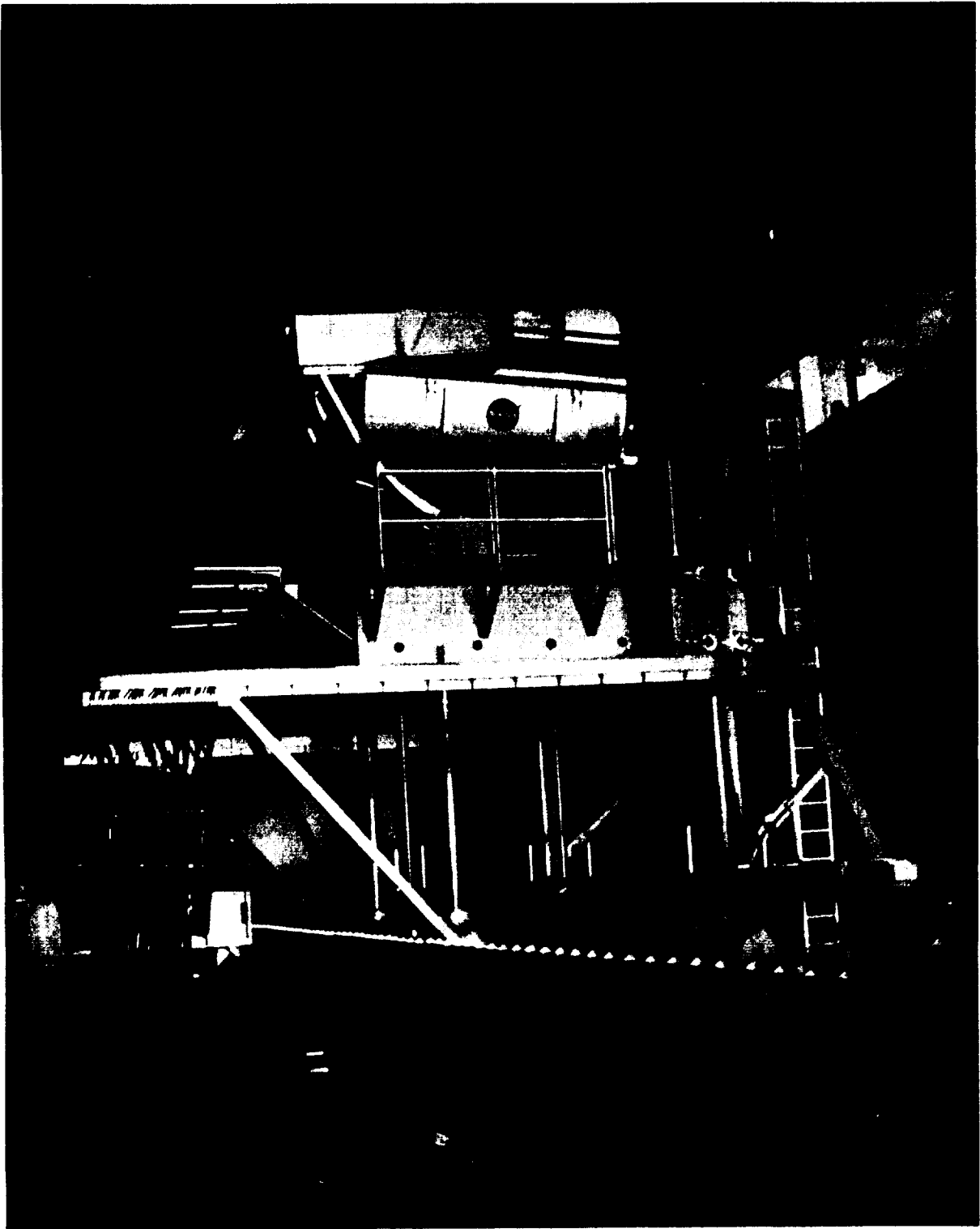
Figure 1.4-1: Motion System and Cockpit of the FSAA

SECTION 2

COMPUTER SYSTEM

2.1 HARDWARE

Hardware other than the cockpit, visual, and motion systems are
described below. Sections 3, 4, and 5 are devoted to the descriptions of
these systems. This section is mainly devoted to the description of
hardware directly linked to the digital computer. The descriptions cover
only those hardware features which are judged potentially important to the
researcher in the planning and conduct of a simulation program.

2.1.1 GENERAL CONFIGURATION

The general configuration of the realtime simulation computer facility
is depicted in Figure 2-1. The figure shows the digital computer and
communication links with all peripheral equipment relevant to realtime
simulations. The digital computer is also used for both timesharing and
batch operations. There is additional peripheral equipment for these
operations which is not shown in Figure 2-1.

Each component of Figure 2-1 is discussed individually in the following
subsections.

2.1.2 DIGITAL COMPUTER

The heart of the simulation facility is the digital computer. It is
used for solving the aircraft equations of motion, interfacing with the
peripheral equipment (see Figure 2-1), and a multitude of other functions.
Solving of the aircraft equations of motion is discussed in the software
section.

Figure 2-1: General Configuration of Realtime Simulation Facility
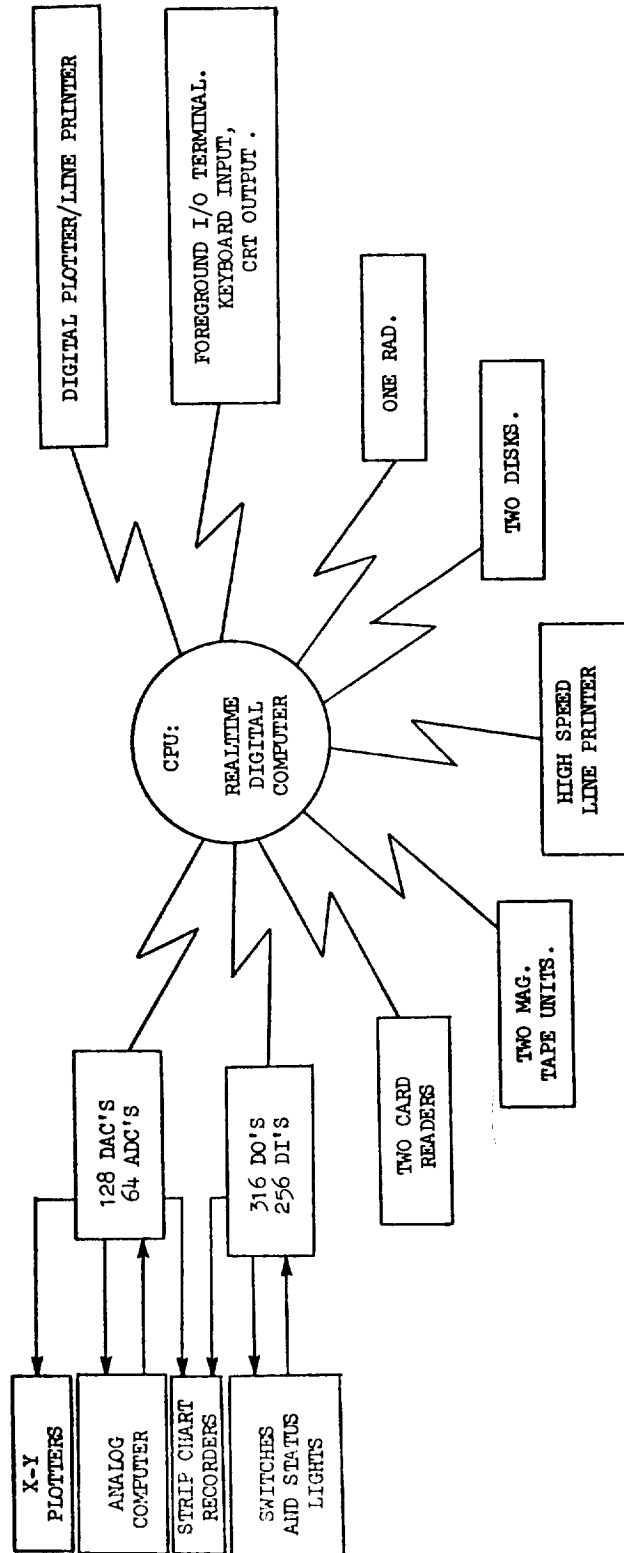
The computer's core memory is partitioned into two areas, the foreground and background. The foreground area is reserved for the realtime simulation user. The background area is reserved for the batch and timeshare user. The foreground user always has priority over all background jobs.

Critical parameters of the digital computer are:

Type: Xerox Sigma-8

Core Size: 128K words for BPM/BTM

Word Size: 32 bits, 8 bit bytes

Cycle Time: 900 ns

Key Execution Times (Single Precision, Floating Point):

Load = .75 μs
Store = 1.77 μs
Add = 2.50 μs
Subtract = 2.50 μs
Multiply = 3.30 μs
Divide = 7.7 to 10.9 μs

2.1.3 PERIPHERAL EQUIPMENT

Foreground I/O Terminal. The foreground I/O terminal forms the main communication link between the user and the digital computer. When used in conjunction with the existing software (see the CASPRE description in Section 2.2.1) the user can monitor and/or change variables within the computer, as well as issue commands (e.g., read a RAD file). The terminal is an HP 2640A with standard typewriter keyboard input and CRT display. Its speed is 1200 Baud (120 characters/second) with optional thermal copy of the last two pages of information displayed on the cathode ray tube (CRT) display.

Digital Plotter/Line Printer. This is the primary foreground output device and as such it may be the researcher's primary means of recording

digital data (e.g., trim conditions, end of run statistics, etc.). As implied, the device can also be used to generate plots (see the VPLOT subroutine description in Section 2.2.3). It is a Versatec Electrostatic Matrix Printer/Plotter using 21.6 cm x 27.9 cm (8 $\frac{1}{2}$ in x 11 in) electrographic paper. Its speed is 300 to 500 lines per minute.

Rapid Access Device (RAD) and Disks. This volatile storage device is primarily used by the Batch Process Monitor/Batch Timesharing Monitor (BPM/BTM) operating system. BPM/BTM uses the RAD to swap foreground and background jobs, and hence release the CPU for batch and timesharing jobs. This swapping is only done while the computer is in the IC mode and does not interfere with realtime operations.

The RAD is very similar to a disk, expect its fixed position read/write head (one per track) makes it access much faster. The RAD storage capacity is 6 megabytes.

Two disks are available for storage of system software, user programs, and data. The foreground user may also read and/or write information on the disk while in the IC mode. This capability can be used to read a set-up deck and to change program variables for different test configurations.

The disks can also provide an indirect link to the high speed printer. The high speed printer is actually a background device and as such is not directly available to the foreground user. This can be circumvented by writing disk files from the foreground area, and then submitting a background job to read these files and print the file contents on the high speed printer.

The storage capacity of each disk is 25 megabytes.

High Speed Line Printer. As mentioned above, this is a background output device and as such is not directly available to the foreground user. However, it can be indirectly used via the process outlined above. It is desirable to use the background line printer for large amounts of data instead of the foreground line printer (the digital plotter described above) because it is much faster.

With the foreground printer, the computer is completely tied up during the printing and no other I/O devices can be serviced. This can cause some

delays between runs as you have to wait for the printing to finish. With the background printer there are no delays to the simulation but the output is not immediately available.

The background line printer speed is 1000 lines per minute.

Magnetic Tapes. Two 9-track, 800 BPI tape units are available. The foreground user can store realtime data on one of the tapes by using the BRUNDM program described in Section 2.2.3. The tapes generated by BRUNDM are referred to as MAC/RAN tapes.

Card Readers. There is one card reader for the background area and one for the foreground area. Their speeds are 1500 and 400 cards per minute, respectively.

The foreground user can directly access the foreground card reader via CASPRE commands (Section 2.2.1). The background card reader can be indirectly used by the foreground user by performing a card-to-disk operation, and then reading the resulting disk file. The reasons for using the indirect method are twofold. First, the background card reader is faster. Second, once the cards have been stored on the disk the data can be used repeatedly without using either of the card readers. This process is especially convenient when it is necessary to change several parameters between runs.

Discrete I/O. Discrete outputs (DO's) and discrete inputs (DI's) provide a means of displaying and changing integer variables within the computer. Typically the discretes are connected to toggle switches and status lights.

Both DO's and DI's are only capable of on/off (i.e., 0 or 1) functions. For example, a SAS on/off toggle switch could be used as input to a DI, and a DO could be used to drive a SAS on/off status light. A number of lights and switches are available at the experimenter's station. The lights can be used to monitor various program options. The switches can be used to control various options even during OPERATE, e.g., engine or other system failures.

There are 128 DI's and 192 DO's. However, not all of these are connected to output stations. The distribution of the more important DI's and DO's is as follows:

32 DI's for computer control console
64 DI's for motion cab
32 DO's for computer control console
48 DO's for motion cab
28 DO's for strip chart recorders

There are other places where the DI's and DO's are used, but in general they are not of practical interest to the researcher.

Digital-to-Analog and Analog-to-Digital Converters (DAC's and ADC's). The DAC's and ADC's provide the computer with the capability of communicating with various analog equipment. For example, the computer commands the motion simulator via DAC's and monitors its position feedback pots via ADC's.

There are 128 DAC's and a 64-channel ADC multiplexer. All are 100 volt, 15 bit converters.

DAC and ADC usage is mostly a function of the researcher's needs. However, the following distribution of ADC's and DAC's are common to all simulations.

NUMBER OF DAC'S	USAGE
9	Redifon Drives
6	Motion Drives
32	Strip Chart Recorders
4	Analog X-Y Plotters
3 to 21	Control Loaders*
1 to 4	Throttle Servos
1 to 4	Engine Sound Generator
1	Airspeed Sound Generator
App. 30	Standard Cab Instruments

* The number of DAC's required by the Control Loaders is a function of the options used by the researcher. See Section 3 for details.

NUMBER OF ADC'S	USAGE
6	Redifon Follow-ups
6	Motion Follow-ups
6	Motion Rates
6	Motion Wrap Around
3	Control Loader Position
3	Control Loader Computed Force
3	Control Loader Actual Force
1 to 4	Throttle Position
2	Brakes
1	Flaps
1	Speed Brake

2.1.4 ANALOG COMPUTERS

There are two EAI 231R analog computers. One is reserved for inter-facing with the control loaders, and one is available for use by the researcher (unless both right and left seat loader systems are being used). The analog computer provides a means for implementing high frequency filters and/or preconditioning analog inputs to the digital computer.

2.1.5 X-Y PLOTTERS AND STRIP CHART RECORDERS

Two analog X-Y plotters are available for plotting realtime data. They are both Electro Instruments, Inc., Model 412 plotters. The plotting area is 27.9 cm x 43.2 cm (11 in x 17 in), and the pen can be commanded up or down by the computer.

Altogether there are six strip chart recorders. Three are used exclusively for recording the states of the motion system. The remaining three are reserved for recording digital variables specified by the re-searcher. The functions of the latter three recorders (i.e., on/off, speed, and scaling) are capable of being controlled locally or by the digital computer.

Each recorder has 8 channels, and each channel of the digitally controlled recorders can be multiplexed. This gives the researcher a maximum of 48 channels for the recording of digital variables. The multiplexing is done by the digital computer.

When using the multiplexing function, the selection of pairs of variables to share each channel must be done carefully. At least one variable of each pair should be a slowly varying signal. Combining two high frequency signals on one channel makes it very difficult to read.

Two of the three digitally controlled recorders have seven event markers each. These event markers are controlled by the DO's and can be positioned at the center, right, or left. These can be used to record various discrete events. All recorders have time markers on both edges in the form of tick marks every second. Time marks are synchronized so that data may be lined up easily.

2.2 SOFTWARE

The software relevant to realtime simulations is discussed below. Functional descriptions of the executive routines and detailed descriptions of the standard and user-supplied realtime subroutines are included, as are the commonly used optional subroutines and utility routines.

2.2.1 EXECUTIVE ROUTINES

The executive routines used for realtime simulations are collectively called FAMILY III. The components of FAMILY III are FATHER, MOTHER, and CASPRE. Their basic functions and relationship to one another are depicted in Figure 2-2. Note that BPM/BTM and the realtime routines are also shown in Figure 2-2. BPM/BTM is the Xerox operating system and will not be discussed in this report.

The realtime routines are discussed in Section 2.2.2. FATHER, MOTHER, and CASPRE are discussed individually in the following subsections.

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BPM/BTM:

BATCH PROCESS MONITOR/BATCH
TIMESHARING MONITOR. THIS IS
THE COMPUTER OPERATING SYSTEM.

FATHER:

PROVIDE SERVICES FOR CASPRE,
MOTHER, AND REALTIME ROUTINES.
INTERFACES WITH THE OPERATING
SYSTEM (BPM/BTM) AND RELEASES
THE CPU WHEN TIME IS AVAILABLE.
PROCESSES ALL FORTRAN RUN-TIME
ERRORS.

REALTIME ROUTINES (BASIC):

DYNAMICS AND KINEMATICS OF THE
AIRCRAFT MODEL.

MOTHER.

REALTIME SCHEDULER AND CLOCK,
REALTIME I/O, AND COMPUTER
MODE CONTROL.

CASPRE:

PROCESSES REQUESTS FROM THE
FOREGROUND I/O TERMINAL.
PROVIDES THE USER WITH THE
CAPABILITY OF MONITORING AND
CHANGING VARIABLES WITHIN
THE COMPUTER.

Figure 2-2: Functions and Relationships of FAMILY III Software.

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2.2.1.1 FATHER

FATHER is the foreground executive consisting of a collection of routines that provide services for MOTHER, CASPRE, and the realtime routines. These services include flow of control, memory management, I/O, processing of Fortran run-time errors, and other functions. Details of these services, however, are of practical interest only to the systems programmer. The realtime simulation user is only rarely aware that FATHER even exists. Hence an explanation of the FATHER capabilities is considered inappropriate to this report.

2.2.1.2 MOTHER

MOTHER is the acronym for Monitor Time Handling Executive Routines. Its primary function is to provide time schedules for realtime, multi-rate simulations. These schedules then determine the flow of execution during the IC, Hold, and Operate modes of operation. Other functions of MOTHER are to monitor the computer mode, act as a realtime clock, and provide realtime I/O.

Each of the above mentioned functions are discussed individually in the following paragraphs.

Scheduling and Modes. MOTHER is a multi-rate scheduler. Many simulations use three loops, with a different frame time for each loop. However, MOTHER can be reconfigured for one or two loops. The following discussion will mainly be limited to the nominal three loop configuration.

The three loops allow functions to be separated according to their relative frequency content. High frequency functions are implemented in loop 1, mid-frequency in loop 2, and low frequency in loop 3.

The method used to execute these loops is a function of the mode of the computer, as shown in Figure 2-3. MOTHER provides an execution schedule for each of the modes shown in Figure 2-3.

The names Slow IC, Fast IC, Loop 1, Loop 2, and Loop 3 used in Figure 2-3 represent the Fortran subroutines SETUP, SLOOPIC, SLOOP1,

NOTE: The functions performed by SLOW IC LOOP, FAST IC LOOP, LOOP1, LOOP2, and LOOP3 are discussed in Section 2.2.2.

Figure 2-3: Functional Block Diagram of MOTHER Initialization and Mode Control.

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SLOOP2, and SLOOP3, respectively. Collectively these subroutines form what is known as BASIC. BASIC is discussed in detail in Section 2.2.2.

The execution schedule for each of the modes is indicated in Figure 2-3.

Mode Control. As shown in Figure 2-3 there are five possible modes of operation, Fast IC, Slow IC, Hold, Operate, and No Mode. The computer mode can be controlled from the computer console, the FSAA, or the motion operator's console, or by software. MOTHER monitors changes to IMODE every period.

The following are succinct summaries of the function of each mode:

- Operate, IMODE=1

  This is the realtime mode of operation. Execution is as shown in Figure 2-4.

- Slow IC, IMODE=-1

  This is the non-realtime mode of the IC function. Initial conditions of all required variables should be set in this mode.

- Fast IC, IMODE=-2

  This is the pseudo-realtime mode of the IC function. Only IC calculations that must be performed in a realtime mode are implemented in this mode (e.g., the motion cab is moved from the center position to the IC position).

- Hold, IMODE=0

  During this mode the states of the simulation program are frozen. The researcher can return to Operate or IC.

A. ONE LOOP, WITH ADC/DAC EVERY Δt_1 SECONDS.

| ADC | LOOP1 | DAC | DI/O | WAIT |

t_n t_{n+1} → REPEAT

ONE PERIOD = $t_{n+1} - t_n = \Delta t_1$
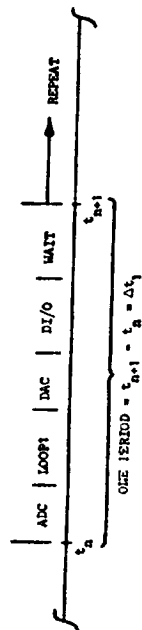
B. TWO LOOPS, 1:2 RATIO, WITH ADC/DAC EVERY Δt_2 SECONDS.

| ADC | LOOP1 | START LOOP2 | LOOP1 | FINISH LOOP2 | DAC | DI/O | WAIT |

t_n t_{n+1} t_{n+2} → REPEAT

ONE PERIOD = $t_{n+2} - t_n = \Delta t_2 = 2\Delta t_1$

C. THREE LOOPS, 1:2:4 RATIO, WITH ADC/DAC EVERY Δt_2 SECONDS.

| ADC | LOOP1 | START LOOP2 | LOOP1 | FINISH LOOP2 | DAC | START LOOP3 | ADC | LOOP1 | START LOOP2 | LOOP1 | FINISH LOOP2 | DAC | FINISH LOOP3 | DI/O | WAIT |

t_n t_{n+1} t_{n+2} t_{n+3} t_{n+4} → REPEAT

ONE PERIOD = $t_{n+4} - t_n = \Delta t_3 = 2\Delta t_2 = 4\Delta t_1$
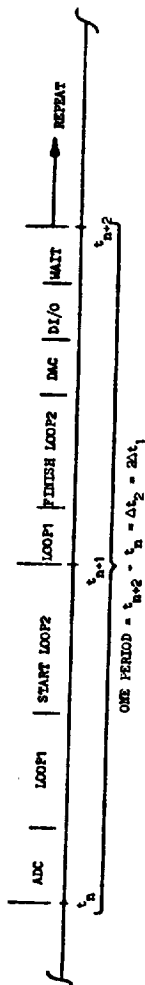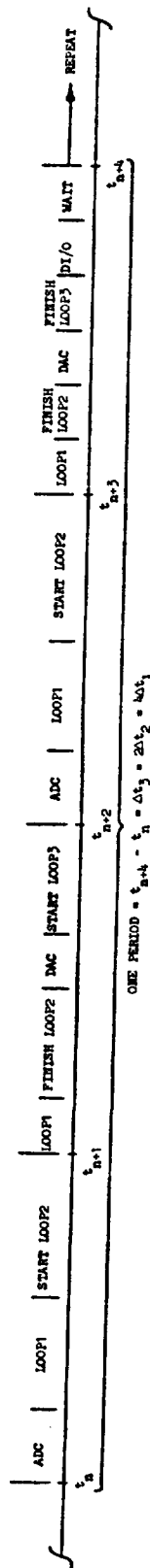
Figure 2-4: Possible Time Lines for Realtime Loop Structures.

     A. One Loop
     B. Two Loops
     C. Three Loops

● No Mode, IMODE=+2

> During this mode, MOTHER performs discrete I/O and checks
> for a mode change. This mode is only internal to the
> computer.

Operate Mode. The Operate loop executes the subroutines SLOOP1,
SLOOP2, and SLOOP3 once every IDT1, IDT2, and IDT3 milliseconds (ms),
respectively. The frame times IDT2 and IDT3 are integer multiples of
IDT1,

$$IDT2=N2*IDT1$$
$$IDT3=N3*IDT1$$

There are practical restrictions on the values of N2 and N3 that will
become apparent in a moment. The default values of N2 and N3 are 2 and 4,
respectively. The default value of IDT1 is 22 ms. Thus the default values
of IDT2 and IDT3 are 44 and 88 ms, respectively.

The method used to execute SLOOP1, SLOOP2, and SLOOP3 is best explained
by way of example. Figure 2-4 depicts time lines over one period of time
for one combination of N2 and N3. One period is the lowest common multiple
of N2 and N3 times IDT1. The practical limitations of N2 and N3 should now
be apparent. N2=2 and N3=4 yield a period of 4*IDT1 ms, but N2=7 and
N3=13 yield a period of 91*IDT1 ms. Discrete I/O is executed only once
per period.

Figure 2-4a depicts the time line for a one-loop simulation. Thus
MOTHER executes LOOP1 every IDT1 ms.

Figure 2-4b depicts the time line for a two-loop simulation with N2=2.
Now MOTHER executes LOOP1 every IDT1 ms and LOOP2 every IDT2 ms. It does
this by first executing LOOP1 and then starting execution of LOOP2. A clock
interrupt signals that IDT1 ms have elapsed. MOTHER executes LOOP1 again
and then finishes the execution of LOOP2, which completes one period. If
there is time left over MOTHER waits before starting another period.*

---

* Actually the CPU is released to the Background if MOTHER has time left
over.

Figure 2-4c depicts the time line for a three-loop simulation with N2=2 and N3=4. The method of execution is similar to the method described for Figure 2-4b.

During the Operate mode MOTHER insures that all computations are completed according to the time schedule. Thus, if the researcher specifies too large a frame time (via IDT1) then MOTHER will wait during some portions of the realtime loop (see Figure 2-4). If the frame time is too small, an error will result and the researcher must increase the value of IDT1. The value of IDT1 is restricted to even integers.

It should be mentioned that the MOTHER initialization routines must be re-executed every time the value of IDT1 is changed. If they are not, a time scaling will result because the time schedule will not be changed. Re-execution of the MOTHER initialization routines is accomplished via CASPRE, as explained in Section 2.2.1.3.

Hold Mode. The Hold loop executes the subroutines SLOOP1, SLOOP2, and SLOOP3 in sequential order for NHOLD times. After NHOLD times through the Hold loop, execution is halted. There is no time constraint. The default value of NHOLD is 10.

IC Mode. Note from Figure 2-3 that there are two IC modes, the Fact IC and the Slow IC. However, both Fast IC and Slow IC loops are executed as Fast IC. The method of execution is depicted by the time line of Figure 2-5.

It is seen from Figure 2-5 that the Fast IC loop is executed once every Δt_{ic} seconds, but that execution of the Slow IC loop is performed on an interactive basis with the Background.

The fast loop frame time, Δt_{ic}, is a function of the motion enables switch, IMCAB. The value of Δt_{ic} is controlled by MOTHER which sets the BASIC variable IDTFST. When IMCAB is zero (i.e., no motion) the value of IDTFST is set such that the Background receives an adequate portion of CPU time. When IMCAB is one (motion enabled) the value of IDTFST is set to NTUSED, the sample rate of the ADC/DAC servicing.

| ADC | FAST IC | DAC | START SLOW IC | RELEASE TO BACKGROUND | ADC | FAST IC | DAC | CONTINUE SLOW IC | RELEASE TO BACKGROUND |
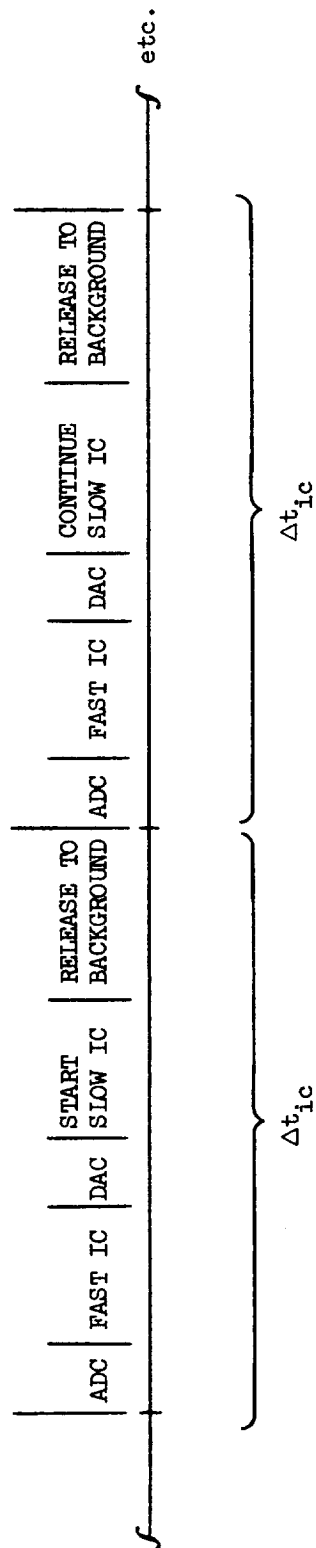
Δt_{ic} is a function of the motion enabled switch, IMCAB, and is controlled by MOTHER. See text for details.

Figure 2-5: Time Line for IC Mode Loop Structure.

The Slow IC loop executes the subroutines SETUP, SLOOP1, SLOOP2, and SLOOP3 in sequential order. There is no time constraint on completion of these loops.

<u>Realtime I/O</u>. Realtime I/O is accomplished via the ADC's, DAC's, DI's, and DO's. The DI's and DO's are serviced at the end of each period. The ADC's and DAC's are normally serviced in the second loop when in Operate, and in the Fast IC loop when in IC.

Note from Figure 2-4 that the ADC's are serviced at the beginning of a frame time and that the DAC's are serviced at the completion of the loop where DAC servicing is specified. Thus DAC output will normally occur after the completion of the LOOP2 computations, but the exact time is not predictable. The approximate execution times for DAC and ADC I/O are 5 and 16 microseconds per channel, respectively.

2.2.1.3 CASPRE

There are two modes to CASPRE, Executive and Debug. Both modes permit the researcher to interface with the computer from the foreground I/O terminal. The functions and capabilities of each CASPRE mode are discussed below.

<u>Executive CASPRE</u>. Executive CASPRE permits the simulation engineer to "log on" to the computer, quit, and access Debug CASPRE. Logging on causes all programs related to the researcher's project to be transferred from the disk to the computer. Quitting terminates the computer session.

In addition, Executive CASPRE allows the operator to save the data associated with the root of the program* on the disk <u>after</u> he has logged

---

* The "root of the program" is that portion of the program which is nominally core resident.

on. The version of the program data saved on the disk may then be restored to the computer by performing a Restore command. The intent of Save and Restore is to provide a convenient way of saving data for short periods of time such that the user can resume his simulation after breaktime (or after a computer failure) without having to duplicate lengthy setup procedures.

Debug CASPRE. Debug CASPRE provides the primary means of checking and modifying variables within the computer program. This is done by simply specifying the Fortran name of any variable whose subroutine was compiled with a symbol table. The relative or absolute address of the variable could be specified instead, but this is usually not as convenient.

Caution should be used when simply specifying the Fortran name of the variable desired. Debug CASPRE will access only the first variable with the specified name. Thus, if there are two or more subroutines that define a variable with the same Fortran name, Debug CASPRE will be able to access only one of the variables.

It is possible that the operator could inadvertently access and/or modify the wrong variable. The best way to avoid this problem is to use descriptive names for the Fortran variables (i.e., avoid using A, B, X, etc.), and to not use any names assigned to the BASIC common (see Section 2.2.2). It is also good practice to verify that a variable has an appropriate value before changing it. An unexpected value may indicate the wrong variable has been accessed.

Debug CASPRE is also used for program initialization, that is, program execution is started at the "ENTER" point of Figure 2-3. Thus, Debug CASPRE causes execution of the MOTHER initialization routines. These routines must be executed every time the loop frame time (IDT1) is changed and when changing the number of ADC's (NAD), DAC's (NDA), DI's (NDI), or DO's (NDO).

Debug CASPRE can also be used to read input data from the foreground card reader or the disk. Data specified in this manner are called Setup Decks. CASPRE output can be directed to the foreground line printer

instead of the foreground I/O terminal, a feature that is useful when a hard copy of a large amount of data is required.

Other capabilities of Debug CASPRE include setting breakpoints (program stops) within any subroutine and the ability to change program instructions (e.g., change an add instruction to a subtract). Both of these features are extremely useful when debugging a new program.

All of the features of Debug CASPRE described above can be used in either the IC, Hold, or Operate modes. However, caution should be used while in the Operate or Hold modes. For example, setting a Breakpoint in Operate would cause execution to be halted. Also, modifications made in Hold have no effect until the mode is changed to either IC or Operate.

2.2.2 SIMULATION ROUTINES

2.2.2.1 GENERAL DESCRIPTION OF BASIC

Realtime simulation of virtually any aircraft model can be implemented via a system of subroutines known as BASIC. BASIC performs functions common to most aircraft simulations. These functions include:

1. Integration of the aircraft equations of motion.
    The form of the equations and axis system used by
    BASIC are summarized in Appendix A.

2. Implementation of commonly used kinematic relationships.

3. Calculation of commonly used aerodynamic parameters.

4. Calculation of commonly used atmospheric parameters.

5. Calculation of commands to the visual system.

6. Calculation of commands to the motion system.

7. Calculation of signals to drive the cab instruments.

8. A means to implement steady state and random gust
    models of the wind.

There are a total of 33 BASIC subroutines used to support the functions described above. These subroutines are normally partitioned with respect to time by calling 6 from the subroutine SLOOP1, 19 from SLOOP2, and 8 from SLOOP3. The subroutines SLOOP1, SLOOP2, and SLOOP3 are in turn called by MOTHER, as described in Section 2.2.1.2.

The primary functions of these three routines are:

SLOOP1: Model the landing gear. Integrate the vertical equation of motion. Note that the vertical equation of motion is in the fastest loop to accommodate the high frequency motions during touchdown.

SLOOP2: Model the high-frequency aerodynamics and control systems. Integrate the horizontal and rotational equations of motion. Support the motion and visual simulators.

SLOOP3: Model the propulsion system, the low frequency aerodynamics and control systems, and miscellaneous low frequency functions.

The BASIC subroutines transfer data between one another primarily via two Fortran Common Lists, XFLOAT and IFIXED. Lists and descriptions of the variables contained in XFLOAT and IFIXED are summarized in Appendix B. The variables contained in these tables are either calculated by the BASIC subroutines or are required inputs to them. Hence, much can be learned about BASIC by studying the contents of Tables B-1 and B-2.

As described in the section on MOTHER, the subroutines SLOOP1, SLOOP2, and SLOOP3 are called in both the Operate and IC modes. Also, the IC mode is partitioned into a realtime loop, Fast IC, and a non-realtime loop, Slow IC. The Fast and Slow IC subroutines are called SLOOPIC and SETUP, respectively. The BASIC subroutines normally called by SLOOP1, SLOOP2, SLOOP3, SLOOPIC, and SETUP are summarized in Figure 2-6 through 2-10. These figures contain succinct descriptions of each BASIC subroutine. More detailed descriptions of the BASIC subroutines are contained in the next section.

Figure 2-6: Subroutines Executed in the First Loop (Called from SLOOP1).

```
                          ┌─────────┐
                         (  ENTER    )
                          ( SLOOP2   )
                          └────┬────┘
                               │
                               ▼
┌─────────────────────────────────────────────────┐
│  SADC:     Enable/disable the ADC's.             │
└─────────────────────────────────────────────────┘
                               │
                               ▼
┌─────────────────────────────────────────────────┐
│  CONTR2:   User supplied model of the high-frequency │
│            components of the control system.     │
└─────────────────────────────────────────────────┘
                               │
                               ▼
┌─────────────────────────────────────────────────┐
│  AERO2:    User supplied model of the high-frequency │
│            components of the aerodynamics.       │
└─────────────────────────────────────────────────┘
                               │
                               ▼
┌─────────────────────────────────────────────────┐          ┌──────────────────────────────┐
│  WINDC:    User supplied model of wind and random │ ───────► │ BWIND:  Implements the MIL-F-8785B │
│            turbulence.                           │ ◄─────── │         model of atmospheric  │
└─────────────────────────────────────────────────┘          │         turbulence.  (Optional) │
                               │                               └──────────────────────────────┘
                               ▼
┌─────────────────────────────────────────────────┐
│  BTORQUE:  Sum the torques acting on the aircraft │
│            due to aerodynamics, the engine, and  │
│            the landing gear.                     │
└─────────────────────────────────────────────────┘
                               │
                               ▼
┌─────────────────────────────────────────────────┐
│  BROTATE:  Compute the angular acceleration of the │
│            aircraft, and integrate the rotational │
│            equations of motions.                 │
└─────────────────────────────────────────────────┘
                               │
                               ▼
┌─────────────────────────────────────────────────┐
│  BTRANSFO: Setup the local-to-body axes          │
│            transformation matrix.                │
└─────────────────────────────────────────────────┘
                               │
                               ▼
┌─────────────────────────────────────────────────┐
│  BHORIZON: Integrate the horizontal equations of │
│            motion.                               │
└─────────────────────────────────────────────────┘
                               │
                               ▼
┌─────────────────────────────────────────────────┐
│  BVELOCIT: Calculate the local-axis and body-axis │
│            components of the aircraft velocity wrt │
│            the air mass.                         │
└─────────────────────────────────────────────────┘
                               │
                               ▼
┌─────────────────────────────────────────────────┐
│  BALFBET:  Calculate the magnitude of the aircraft │
│            velocity wrt the air mass, and the angles │
│            of attack, and sideslip.              │
└─────────────────────────────────────────────────┘
                               │
                               ▼
┌─────────────────────────────────────────────────┐
│  BACCELER: Compute the specific forces at the    │
│            aircraft c.g. and the pilot's station. │
└─────────────────────────────────────────────────┘
                               │
                               ▼
                         To Figure 2-7
                         (concluded)
```

Figure 2-7: Subroutines Executed in the Second Loop. (Called from SLOOP2).

From
Figure 2-7

SHOW: User supplies. Used for realtime
         data collection.

UTIL2:   Used for implementing any special
         purpose high-frequency features.

INS10A: Process any special
          purpose high-frequency
          signals required by the
          cab instruments.

BVISUAL: Calculate commands to the
           visual system.

BMOTION: Monitors and sets various motion status
           switches, and pre-conditions the input
           to the motion washout routine.

BBEND: Implements the motion
         washout logic, and
         calculates the commands
         to the motion system.

SDAC: Implements the logic used for
        multiplexing the strip chart DAC's.

RETURN TO
MOTHER

Figure 2-7:   (Concluded)

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Figure 2-8: Subroutines Executed in the Third Loop. (Called from SLOOP3).

```
        ┌──────────────┐
        │    ENTER     │
        │   SLOOPIC    │
        └──────┬───────┘
               │
               ▼
┌───────────────────────────────────┐          ┌───────────────────────────────┐
│ BMOTION:   Move the motion cab from│─────────▶│ BBEND:   See Figure 2-7.      │
│            the center position (CP)│◀─────────│                               │
│            to the IC position.     │          │                               │
└───────────────┬───────────────────┘          └───────────────────────────────┘
                │
                ▼
┌───────────────────────────────────┐
│ BVISUAL:   Move camera to the IC   │
│            position.               │
└───────────────┬───────────────────┘
                │
                ▼
┌───────────────────────────────────┐
│ SDAC:      See Figure 2-7.         │
│                                    │
└───────────────┬───────────────────┘
                │
                ▼
        ┌──────────────┐
        │  Return to   │
        │    MOTHER    │
        └──────────────┘
```
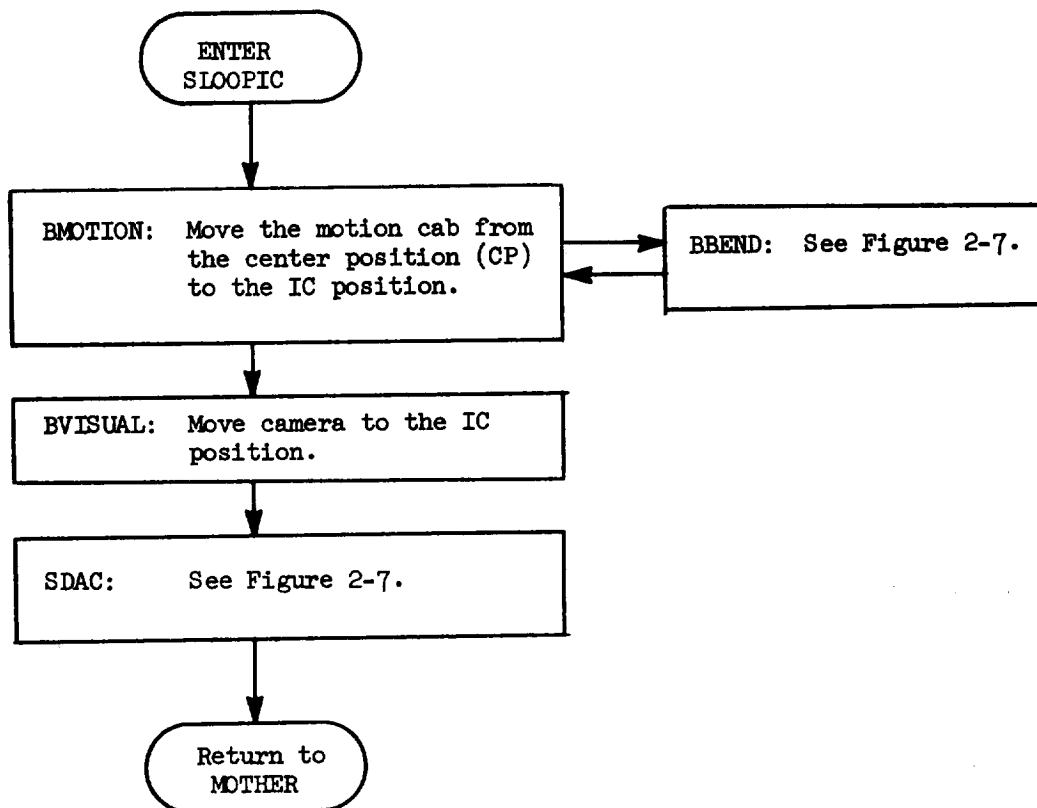
Figure 2-9: Subroutines Executed in the Fast IC Loop. (Called from SLOOPIC).

```
                    ┌─────────────┐
                   (    ENTER      )
                    └─────────────┘
                          │
                          ▼
        ┌──────────────────────────────────┐
        │  SETUP:   User supplied.  Imple-  │
        │           ments any "IC only"     │
        │           features.  Calls        │
        │           BSETUP.                 │
        └──────────────────────────────────┘
                          │
                          ▼
   ┌──────────────────────────────┐      ┌────────────────────────────────┐
   │  BSETUP:  Initializes all     │─────▶│  BATMOSPH:   See Figure 2-8.   │
   │           velocity            │◀─────│                                │
   │           and position        │      └────────────────────────────────┘
   │           integrators.        │      ┌────────────────────────────────┐
   │           Calculates the      │─────▶│  BVELOCIT:   See Figure 2-7.   │
   │           coeffi-             │◀─────│                                │
   │           cients of moments of│      └────────────────────────────────┘
   │           inertia and         │      ┌────────────────────────────────┐
   │           coefficients        │─────▶│  BALFBET:    See Figure 2-7.   │
   │           of angular momentum │◀─────│                                │
   │           of rotating         │      └────────────────────────────────┘
   │           machinery.          │
   └──────────────────────────────┘
                  │
                  ▼
        ┌──────────────────┐
        │     SLOOP1        │
        └──────────────────┘
                  │
                  ▼
        ┌──────────────────┐
        │     SLOOP2        │
        └──────────────────┘
                  │
                  ▼
        ┌──────────────────┐
        │     SLOOP3        │
        └──────────────────┘
                  │
                  ▼
           ┌──────────────┐
          (   Return to    )
          (    MOTHER      )
           └──────────────┘
```

Figure 2-10:   Subroutines Executed in the Slow IC Loop.

2.2.2.2 DETAILED DESCRIPTIONS OF THE BASIC SUBROUTINES

Detailed descriptions of all the BASIC subroutines are contained below. The descriptions are divided into subroutines called by the three operate loops (SLOOP1, SLOOP2, and SLOOP3), the Fast IC loop (SLOOPIC), and the Slow IC loop (SETUP).

There are two formats used to describe the subroutines. The first is used for very short subroutines that perform only one or two functions. For these only a one- or two-sentence description is given. The second format is used for the more complex, multi-function subroutines. The format for these subroutines is to list their primary functions, all inputs, all outputs, and any special features.

FIRST LOOP SUBROUTINES, SLOOP1

BFTOTAL:

Sums the body axis components of the applied forces acting on the aircraft due to the engines, aerodynamics, and landing gear. Outputs are FTX, FTY, FTZ.

BVERTICA:

Primary Function:

Integrates the vertical equation of motion.

Program Inputs:

1. The Local-to-Body axes transformation matrix (T11 $\longrightarrow$ T33).

2. The mass of the aircraft (XMASS) and the force due to gravity (FG).

3. Total applied force acting on the aircraft (FTX, FTY, FTZ).

4. Past value of the aircraft velocity wrt the Local axis (VE, VN, VD).

5. Radius from center of the earth to the aircraft c.g. (RTV).

6. Past value of the aircraft altitude wrt sea level (ALT).

7. Runway elevation wrt sea level (HR).

8. Location of the right main gear wrt the aircraft body axis system (XRG, ZRG).

9. Sine and cosine of the aircraft pitch attitude (STHT, CTHT).

Program Outputs:

1. Vertical component of the applied force acting on the aircraft in the Local axis system (FD).

2. Total downward acceleration in the Local axis system (VDD).

3. Vertical velocity in the Local axis system (VD=-ALTD).

4. Altitude of the aircraft c.g. wrt sea level (ALT) and the runway (HCG).

5. Altitude of the main gear wrt the runway (HWEEL).

Special Features:

1. Flat Earth Option (IFLAT). If IFLAT=0 then VDD is computed for round earth. If IFLAT=1 then VDD is computed for a flat earth.

2. Fixed Flight Debug Option (IFFCI). If IFFCI=1 then the integrations that compute the vertical velocity and position are not performed.

BLGA:

Computes the height and rate of the aircraft tail wrt the runway (HTAIL, HTAILD), and sets the tail strike switch (IHIT). Computes the gear strokes and stroke rates (AWEEL(I), AWEELD(I)). The kinematic equations used to make the above computations are contained in Reference 5.

GEARS:

User supplied subroutine. Computes the normal, side, and drag forces on each gear wrt the runway axis system (FOLEO(I), FSIDE(I), FRICT(I)). Also computes the normal and drag forces due to a tail

strike (FRTAIL, FRICTT). Inputs are a function of model details, but typically will include gear strokes and stroke rates, oleo strut spring constants and damping coefficients, coefficients of friction, nose wheel steering and brake deflections. See Reference 1 for a description of a typical gear model.

BLGB:

Transforms the forces acting on each gear to the aircraft body axis system (FRXP(I),FRYP(I),FRZP(I)). Zeros the appropriate components for the gear which are not in ground contact.

BLGC:

Computes the total body axis components of the applied forces (FGX, FGY, FGZ) and torques (TGX, TFY, TGZ) acting on the aircraft due to the landing gear and tail strike.

SECOND LOOP SUBROUTINES, SLOOP2

SADC:

Turns off the ADC's when the aircraft is trimming (NADIN=0). Turns them on when not trimming (NADIN=1).

CONTR2:

User supplied subroutine. Used for implementing the high frequency components of the control systems model (e.g., elevator, aileron, rudder).

Program inputs are the pilot commands (control column, rudder pedals, etc.) required for the manual control system, and/or aircraft states (Θ, Q, Φ, etc.) required for the SAS or automatic system. Program outputs are the aerodynamic control surface deflections.

AERO2:

User supplied subroutine. Used for implementing the high frequency components of the aerodynamic model. Typically these are the moment

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equations, and hence program outputs are the body axis components
of the applied torque acting on the aircraft due to aerodynamic
loads (TAL,TAM,TAN). Program inputs are the control surface de-
flections and aircraft states used by the aerodynamics model.

WINDC:

User supplied subroutine. Used for modeling the wind (VNW,VEW,VDW)
and random turbulence (UTURB,VTURB,WTURB). The wind components are
in the Local axis system. The turbulence components can be modeled
in either the aircraft body axis or the Local axis system (IETURB=0
or 1, respectively).

The wind components are typically programmed to be functions of
either time or position, or simply be constants. The turbulence
components are usually implemented via the BWIND subroutine (see
below).

The sign convention of the wind components is positive toward.
Thus an "easterly" wind (+ VEW) is a wind toward the east. The
sign of the turbulence components is positive in the usual sense
of the aircraft body axis system.

BWIND:

This is a BASIC subroutine that models the MIL-F-8785B (Reference 2)
version of atmospheric turbulence. The subroutine WINDC must supply
BWIND with the scale lengths and RMS gust levels for each of the
three components. A complete description of BWIND can be found in
Reference 3. The outputs are three gust components (UTURB,VTURB,
WTURB) and three equivalent angular rates (PTURB,QTURB,RTURB) for
gust gradient effects.

BTORQUE:

Sums the body axis components of the applied torques acting on the
aircraft due to the engines, aerodynamics, and landing gear (TTL,TTM,
TTN).

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BROTATE:

Primary Function:

Integrates the rotational equations of motion.

Program Inputs:

1. The body axis components of the total applied torque acting on the aircraft (TTL,TTM,TTN).

2. The past values of the body axis components of the angular velocity wrt inertial space (PB,WB,RB).

3. Coefficients of moments of inertia (XMC(I),I=1 to 10). See Appendix A for definitions.

4. Coefficients of angular momentum of rotating machinery. See Appendix A for definitions.

5. The body axis components of the equivalent angular velocity due to turbulence (PTURB,QTURB,RTURB).

6. The past values of the aircraft Euler angles (PSI,THET,PHI).

7. The body axis components of the angular velocity of the local coordinate system wrt inertial space (PLB,WLB,RLB).

Program Outputs:

1. The body axis components of the aircraft acceleration wrt inertial space (PBD,QBD,RBD).

2. The body axis components of the angular velocity wrt inertial space (PB,QB,RB).

3. The body axis components of the aircraft angular velocity wrt the Local axis system (PT,QT,RT).

4. The body axis components of the angular velocity wrt inertial space plus the angular velocity due to turbulence (PBWN,QBWN,RBWN).

5. Aircraft Euler angle rates (PSID,THED,PHID).

6. Aircraft Euler angles (PSI,THET,PHI).

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Note:

Both the coefficients of moments of inertia and angular momentum of
rotating machinery are only calculated in the IC mode (viz, BSETUP).
If the user wants either of them to change during the mode (e.g.,
due to spinup or spindown of the engines), then they must be calcu-
lated somewhere in the Operate loop, for example, XMCC1 to XMCC7
could be calculated in the ENGINE subroutine.

BTRANSFO:

Calculates the sine and cosine of all Euler angles. Calculates the
components of the T11 ——➤ T33 Local-to-Body axis transformation
matrix.

BHORIZON:

Primary Function:

Integrates the horizontal equations of motion, and computes the
pilot position wrt the runway.

Program Inputs:

1. The Local-to-Body axis transformation matrix (T11 ——➤ T33).

2. The mass of the aircraft (XMASS).

3. Radius from center of the earth to the aircraft c.g. (RTV).

4. Radius from center of the earth to the runway (RR).

5. Total applied force acting on the aircraft (FTX,FTY,FTZ).

6. Past values of aircraft inertial velocity components in Local
    axes (VN,VE,VD).

7. Past values of the aircraft longitude and latitude (XLON,XLAT).

8. Location of the pilot wrt the aircraft body axis system (XP,YP,ZP).

Program Outputs:

1. The north and east components of the total applied force acting
    on the aircraft (FN,FE).

2. The derivatives of the north and east components of the aircraft
    velocity (VND,VED).

3. The north and east components of the aircraft inertial velocity (VN,VE).

4. The east component of aircraft velocity wrt the earth's surface (VEE).

5. Aircraft latitude and longitude rates (XLATD,XLOND).

6. Aircraft latitude and longitude (XLAT,XLON).

7. The north and east coordinates of the aircraft c.g. and pilot station wrt the runway (DNR,DER,DNPR,DEPR).

8. The coordinates of the pilot station in the runway axis system (XPR,YPR,HPR).

Special Features:
1. Flat Earth Option (IFLAT). If IFLAT=0 then VND and VED are computed for a round earth, and the velocity VEE is corrected for the rotation of the earth. If IFLAT=1, then VND and VED are computed for a flat earth and VE=VEE.

2. Fixed Flight Debug Option (IFFCI). If IFFCI=1 then the integrations that update velocities and positions are not performed.

BVELOCIT:

Transforms the turbulence components from body axes (UTURB,VTURB, WTURB) to the Local axis system (VNTURB,VETURB,VDTURB) if IETURB=0. Does reverse if IETURB=1. Computes the sum of the wind and turbulence components (VTWN,VTWE,VTWD). Computes the velocity of the aircraft wrt the air mass in local and body axes systems (VNR,VER,VDR; UB,VB,WB).

BALFBET:

Computes the angles of attack, α, and sideslip, β (ALFA,BETA ~ deg; ALFAR,BETAR ~ rad). Computes the sines and cosines of α and β (SALPH, CALPH;SBETA,CBETA). Calculates the magnitude of the velocity of the aircraft wrt the air mass (VRW). Calculates the derivative of the

aircraft velocity wrt the air mass in the body axis system (UBD, VBD, WBD). Calculates the derivatives of α and β (ALPD, BETD).

BACCELER:

Computes the specific forces (accelerometer outputs) at the aircraft center of gravity and pilot station in the body axis system (AXCG, AYCG, AZCG, AXP, AYP, AZP).

SHOW:

User supplied subroutine. Used for realtime data collection. Typically this subroutine is used in conjunction with a print subroutine. SHOW is core resident and performs only those operations necessary while the computer is operating in the realtime mode. The print subroutine is accessed via an overlay scheme, and is only used while the computer is in the IC mode. The purpose is to have one subroutine collect the required data, and to have the other process and output the data. This scheme makes the most efficient use of the computer and increases the amount of realtime data that can be collected.

UTIL2:

User supplied subroutine. Calls the high frequency cab instrument support subroutine (INS10A for the FSAA). Can be used to implement any special purpose high frequency features (e.g., process special variables to be recorded on the strip charts, call the dynamic check subroutine, etc.).

INS10A:

This is actually a system subroutine that is sometimes specially tailored to meet the needs of a particular simulation. Its purpose is twofold. One is to call the BVISUAL subroutine (see below), and the other is to support some of the cab instruments. Which instruments depends, in general, on the aircraft being simulated. The only instrument command signal that is always calculated by INS10A is for the HSI (PSIDR).

BVISUAL:

Calculates the commands to the visual system. Program inputs are
the linear position and angular orientation of the pilot station
wrt the runway axis system (XPR,YPR,HPR;PSI,THET,PHI and ceiling
height). Outputs are linear and angular commands. See Section 4.2
for more details regarding this subroutine.

BMOTION:

Primary Function:

Implements the logic required to interface with the motion simulator.
This entails the monitoring and setting of various status switches,
preconditioning the inputs to the motion drive subroutine (BBEND),
and calling the motion drive subroutine.

Program Inputs:

1. The motion enable switch, IMCAB. This is activated by the
computer operator when motion is required.

2. The motion drive rack status switch, LOOPDR. This switch is
activated when the motion operator closes the loops that connect
the motion drive rack to the simulator.

3. Computer mode switch, IMODE.

4. Motion drive rack enabled switch, IDRENB. This switch is
activated when the motion operator closes the loops that
connect the computer to the motion drive rack.

5. The motion command signals (CMOT(I),I=1 to 6), and the output
of the "wrap-around" ADC's (WAMOT(I),I=1 to 6). The differences
between CMOT(I) and WAMOT(I) are used to determine if the
motion DAC's are working properly.

6. The cab rates (from tachometers, TACHMOT(I),I=1 to 6). These
are used to determine if the cab has reached the IC position.

7. Flexible aircraft switch, IFLEX. This option provides a means
of simulating body bending. It causes an alternate set of body

axis angular accelerations to be input to the motion drive sub-routine. The Fortran variables are:

$$\dot{p}_B = PBDPL, \ rad/sec^2$$

$$\dot{q}_B = QBDPL$$

$$\dot{r}_B = RBDPL$$

Calculations must be done by the user, and should be made compatible with the incremental Euler angles that drive the visual system (see BVISUAL).

8. The specific forces and angular accelerations at the pilot station in the aircraft body axis system (AXP,AYP,AZP;PBD,QBD,RBD).

Program Output:

1. The switch that enables the motion simulator to go to the "IC position", ICENAB. The IC position differs from the center position (CP) because of residual tilts (e.g., $a_x \longrightarrow \theta_{sim}$). The switch is activated only after it has been determined that the motion DAC's are working properly (i.e., CMOT(I) - WAMOT(I) are within error criteria).

2. The switch that gives mode control of the computer to the motion operator, MODENB. This switch is activated only after the cab has reached its IC position (i.e., TACHMOT(I) are close to zero).

3. Inputs to the motion drive subroutine, BBEND (AMOT(I),I=1 to 6). In the Operate mode these are the specific forces and angular accelerations at the pilot station.

Special Features:

Slow return of the motion simulator to the IC position. This is done to avoid large and unnecessary accelerations of the motion simulator. It is accomplished by filtering the computer commands to return to the IC position. Note that BMOTION is in the Fast IC loop. Thus the filtering is done in a realtime mode.

BBEND:

Implements the motion washout logic, and calculates the commands to the motion system. Program inputs are the specific forces and angular accelerations at the pilot station in the aircraft body axis system (AXP,AYP,AZP;PBD,QBD,RBD). Outputs are linear and angular rate commands. See Section 5.2 for more details regarding this subroutine.

SDAC:

Implements the logic for multiplexing the DAC's used by the strip chart recorders.

THIRD LOOP SUBROUTINES, SLOOP3

BATMOSPH:

Primary Functions:

Computes pressure, density, and temperature properties as functions of altitude and Mach number. Density and speed of sound are based on the 1962 ARDC model atmosphere. Also computes impact pressure, dynamic pressure, equivalent airspeed, and calibrated airspeed.

Program Inputs:

1. Altitude wrt sea level (ALT).

2. Magnitude of the aircraft velocity wrt the air mass (VRW).

Program Outputs:

1. Density and speed of sound at sea level (RHOZ,SOUNDZ).

2. Density and speed of sound at altitude (RHO,SOUND).

3. Mach number (XMACH).

4. Ratios of total to ambient temperature and pressure (TR,PR).

5. Ratios of ambient to sea level temperature and pressure (TAMBR, PAMBR).

6. Ambient temperature (deg K) and pressure (lb/ft^2), (TAMB,PAMB).

7. The total temperature (deg K) and pressure (lb/ft^2), (TTOT,PTOT).

8. Impact pressure (lb/ft^2), (QBARC).

9. Dynamic pressure (lb/ft^2), (QBAR).

10. Equivalent airspeed (VEQ ~ kt).

11. Calibrated airspeed (VCAL ~ kt).

Special Features:

1. Constant density atmosphere switch (ICOND). If ICOND=1 then all the parameters listed in the program output section above are calculated at only one altitude, HRHOZ. HRHOZ is set by the user; its default value is zero.

2. Modify the ambient density and speed of sound by a delta-temperature effect (DELAT). See page 22 of Reference 5 for details. The user is responsible for supplying temperature increment.

BEARTH:

Calculates the X and Y coordinates of the aircraft center of gravity wrt the runway axis system (XCG,YCG). Calculates the sine, cosine, and tangent of the aircraft's latitude (SLAT,CLAT,TLAT). Calculates the acceleration due to gravity (G) at the aircraft's altitude and the force due to gravity (FG).

BINERTIA:

Calculates the angular velocity of the local axis system wrt inertial space (PL,WL,RL in Local axis system; PLB,WLB,RLB in aircraft body axis system). If the flat earth option is on (IFLAT=1) then all the above angular velocities are set to zero. Calculates the magnitude of the velocity vector wrt the surface of the earth (VT). Calculates the ground speed (VG). Calculates the inertial flight path angles in the vertical and horizontal planes (GAMV,GAMH).

CONTR3:

User supplied subroutine. Used for implementing the low frequency components of the control system model (e.g., flaps, landing gear, trimming devices). Program inputs are the pilot commands (flap handle, gear lever, etc.) required for the manual control system, and/or aircraft states (Θ, Q, Φ, etc.) required for the SAS or automatic system. Program outputs are the control surface deflections.

ENGINE:

User supplied subroutine. Used for implementing the propulsion system model. The dynamics of the propulsion system are usually low frequency, and hence implementation in the third loop is adequate. However, if this is not the case for a particular model, the propulsion system model can be moved to SLOOP2. Program inputs can include throttle positions, failure switches, aircraft state, and atmospheric properties. Program outputs must include the body axis components of the applied torque (TEL,TEM,TEN) and force (FEX,FEY,FEZ) acting on the aircraft due to the propulsion system, and parameters to drive engine instruments in the cab, such as RPM and EPR.

AERO3:

User supplied subroutine. Used for implementing the low frequency components of the aerodynamic model. If these are the force equations, the program outputs must include the body axis components of the applied force acting on the aircraft due to aerodynamic loads (FAX, FAY,FAZ). AERO3 can also be used to update coefficients or tables in AERO2 which are functions of slowly varying parameters, such as flap or Mach number. Program inputs are the control surface deflections and aircraft states used by the aerodynamics model.

UTIL3:

User supplied subroutine. Calls the low frequency cab instrument support subroutine (INS10B for the FSAA). Can be used to implement any special purpose low frequency features (e.g., process special variables to be recorded on the strip charts).

INS10B:

Primary Functions:

Commands some of the low frequency cab instruments. Sets the status of miscellaneous switches. Controls the strip chart recorders. Processes special strip chart variables. Models the landing gear up/down logic.

Program Inputs:

1. Location of the glide slope and localizer receivers wrt the aircraft body axis (XBGS,YBGS,ZBGS;XBLOC,YBLOC,ZBLOC).

2. Location of the glide slope and localizer transmitters wrt the runway axis (XPGS,YPGS;XPLOC,YPLOC).

3. Coordinates of the outer and middle markers wrt the runway axis (XOM,YOM;XMM,YMM), and the half angle that they subtend (AMEG, default is 27.25 deg).

4. Coordinates of the aircraft c.g. and pilot station wrt the runway axis (XCG,YCG,HCG;XPR,YPR,HPR).

5. Height of main gear above runway (HWEEL).

6. Flare initiation altitude (HFLARE).

7. Glide slope transmitter angle (THETGS).

8. Aircraft rate of climb and altitude wrt sea level (ALTD,ALT).

9. Calibrated airspeed (VCAL), and the X-component of the aircraft velocity wrt the air mass (UB).

10. Parameters for controlling the strip chart recorders:
    a. Numbering option and run number (INUMBR,NRUN).
    b. Chart speed as a function of altitude (SCSPDA,SCSPDB,HTSCSW).

11. Landing gear deployment parameters:
    a. Command gear up or down switch (IWEELC).
    b. Gear transit times to move up and down (GUTIM,GDTIM).

12. Aircraft center of gravity wrt the leading edge of the MAC (CG).

Program Outputs:

1. Instrument signals.

   a. Angular glide slope error (EPSGS).

   b. Angular localizer error (EPSLOC).

   c. Distance from the glide slope transmitter to the pilot station (DME).

   d. Indicated airspeed. There are provisions for driving up to three airspeed instruments. Typically these are:
      (1) Pilot station (VIAS1).
      (2) Copilot station (VIAS5).
      (3) Project engineer console (VIAS3).

      To provide for nonlinearities, each instrument is driven via a table look-up scheme. Input to the pilot's and project engineer's tables is the calibrated airspeed (VCAL). Input to the copilot's table is the X-component of the aircraft velocity wrt the air mass (UB). Outputs are the voltages used to drive the instruments. Linear interpolation is used to obtain the indicated airspeed between the table entries.

   e. Alternate indicated airspeed. Calculates the inputs to a continuous resolver type airspeed indicator. See program listing for details.

   f. Center of gravity instrument. Displays the aircraft center of gravity wrt the leading edge of the MAC (CGINS=CG-56).

   g. Instantaneous Vertical Speed Indicator (IVSI). Instrument is nonlinear, and hence uses a table look-up scheme. Table input is the aircraft rate of climb (ALTD); output is the voltage used to drive the instrument (HDOTI).

   h. Radio altimeter. Instrument is nonlinear, and hence uses a table look-up scheme. Table input is the aircraft wheel height wrt the runway (HWEEL); output is the voltage used to drive the instrument (HRADIO).

2. Miscellaneous Status Switches:

   a. Over outer and middle markers (IOM,IMM).

   b. Aircraft below 457.2 m (1500 ft) and 61.0 m (200 ft) altitude wrt the runway (I1500,I200).

   c. Aircraft below the flare initiation altitude (IFLARE).

3. Control of the strip chart recorders:

   a. Turn the recorders on in Operate, off in IC.

   b. Set the chart speed as a function of the aircraft altitude:

$$\text{SPEED} = \begin{cases} \text{SCSPDA mm/sec for } h \geq \text{HTSCSW} \\ \text{SCSPDB mm/sec for } h < \text{HTSCSW} \end{cases}$$

   c. Label the strip charts (option, do if INUMBR=1). The run number (NRUN) is written on the first three channels of each strip chart recorder at the end of a run.

4. Special strip chart variables. For the purpose of maintaining reasonable recording sensitivities throughout a large operating region the following aircraft states are specially treated:

   a. Altitude. Two methods of recording the aircraft altitude are provided:

      (1) Variable sensitivity.

$$\text{HREC} = \begin{cases} 15.7 \text{ m/line (50 ft/line) for} & h \leq 762 \text{ m (2500 ft)} \\ 76.2 \text{ m/line (250 ft/line) for } 2500 < h \leq 4572 \text{ m (15000 ft)} \\ 304.8 \text{ m/line (1000 ft/line) for } 15000 < h \leq 19812 \text{ m (65000 ft)} \end{cases}$$

      (2) Variable limits.

$$\text{HFINE} = \text{HWEEL} - \text{INT}\left(\frac{\text{HWEEL}}{\text{ALTMOD}}\right)\text{ALTMOD}.$$

Where the variable ALTMOD is set by the user. Using this method the recorder limits are varied as a function of altitude. Thus if ALTMOD were

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76.2 m (250 feet) and HWEEL were 243.8 m (800 feet) then the recorder limits would be 228.6 m (750 feet) to 304.8 m (1000 feet) (the sensitivity would be a constant 1.52 m/line (5 feet/line)).

b. Airspeed. The variable limits method is available for recording calibrated airspeed

$$VFINE = VCAL - INT\left(\frac{VCAL}{VMOD}\right) VMOD$$

Where VMOD is set by the user. The recorder limits are varied as a function of calibrated airspeed, but the sensitivity is constant. Thus if VMOD were 25.7 m/sec (50 kt) and VCAL were 66.9 m/sec (130 kt), then the recorder limits would be 30.5 m (100 feet) to 45.7 m (150 feet). (The sensitivity would be 0.51 m/sec-line (1 kt/line)).

c. Distance. The variable sensitivity method is used for recording the X-distance of the aircraft c.g. wrt the runway threshold,

$$XREC = \begin{cases} 152.4 \text{ m/line (500 ft/line) for } |XCG| \leq 3810 \text{ m (12500 ft)} \\ 609.6 \text{ m/line (2000 ft/line) for } |XCG| > 3810 \text{ m (12500 ft)} \end{cases}$$

Note. Additional variables may be specially processed for recording by using either UTIL2 or UTIL3 to implement the required algorithms.

5. Landing gear up/down status lights. The gear position is commanded via the switch IWEELC (0 for up, 1 for down). The gear status is monitored by the switch IWEEL (0 for up, 1 for down). The gear travel times are controlled by the variables GUTIM (time from the down to the up position, sec) and GDTIM (from the up to the down position). When the gear is in transit the switch ILGTRN is set to one.

6. Pulse the cycle switch (ICYCLE). This switch is alternately set to one or zero each pass through this program. Since this

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is the last program in the third loop, this switch signifies
the completion of one period. ICYCLE is used by the motion
simulator to determine if the digital computer is still
functioning.

FAST IC SUBROUTINES, SLOOPIC

BMOTION:

This is the same subroutine as described in the second loop (SLOOP2)
section. When in the Fast IC mode the motion command signals are
filtered with first order lags. This prevents large accelerations
of the cab when going from the center position to the IC position,
or returning to IC from Operate.

BVISUAL:

This is the same subroutine as described in the second loop (SLOOP2)
section.

SDAC:

This is the same subroutine as described in the second loop (SLOOP2)
section.

SLOW IC SUBROUTINES

SETUP:

User supplied subroutine. Its purpose is to implement any special
purpose, IC only, model features, and call the subroutine BSETUP.
For example, calculate the aircraft inertias as functions of weight
and c.g. A few other possibilities are:

1. Call the trim subroutine, BQUIET.
2. Call the instrument scaling subroutine, INSCAL.
3. Call the stability derivative subroutine, STABLE.

All of the above subroutines are optional features.

BSETUP:

Primary Functions:

Initializes all velocity and position integrators. Calculates the coefficients of moments of inertia and coefficients of angular momentum of rotating machinery. These coefficients are defined in Appendix A.

Program Inputs:

1. The initial orientation of the aircraft. This is, the aircraft Euler angles (PSIIC,THETIC,PHIIC ~ deg).

2. The initial position of the aircraft c.g. or pilot station wrt the runway origin (XIC,YIC,HIC ~ ft)

3. Angle of the runway centerline from north (THTRR ~ deg).

4. Latitude and longitude of the runway origin (XLATR,XLONR ~ rad).

5. The "initial" aircraft moments of inertia (XIXXIC,XIYYIC,XIZZIC, XIXZIC ~ slug-ft^2)*.

6. The "initial" aircraft weight (WAITIC ~ lb).*

7. The "initial" angular momentum of rotation machinery (EXMX,EXMY, EXMZ ~ slug-ft^2).*

8. Coordinates of the pilot station wrt the aircraft body axis system (XP,YP,ZP ~ ft).

9. The initial body axis angular velocity of the aircraft (PBIC,QBIC, RBIC ~ deg/sec).

10. The initial inertial flight path angles in the vertical and horizontal planes (GAMVIC,GAMHIC ~ deg).

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* There is no provision for changing the aircraft weight, moments of inertia, or angular momentum of rotating machinery in the realtime mode. Therefore, if a user desires to simulate these changes he must implement the proper equations in the realtime loop. For example, the ENGINE or UTIL3 subroutines.

11. Altitude of the runway origin wrt sea level (HR ~ ft).

12. Radius of the earth (RE = 6,369,987.16 m (20,898,908 ft)).

13. North, east, and down components of the wind (VNW,VEW,VDW ~ ft/sec).

14. The initial equivalent airspeed (VEQIC ~ kt).

Program Outputs:

1. The aircraft Euler angles (PSI,THET,PHI ~ deg;
   PSIR,THETR,PHIR ~ rad).

2. Altitude of the aircraft c.g. wrt sea level (ALT ~ ft) and the
   runway (NCG ~ ft).

3. Altitude of the pilot station wrt the runway (HPR ~ ft).

4. Latitude and longitude of the aircraft c.g. (XLAT,XLON ~ rad).

5. Radius of aircraft c.g. from the center of the earth (RTV ~ ft).

6. Radius of runway origin from the center of earth (RR ~ ft).

7. Body axis angular velocity (PB,QB,RB ~ rad/sec).

8. Aircraft Euler angle rates (PHID,THED,PSID ~ rad/sec).

9. Inertial flight path angles in the vertical and horizontal
   planes (GAMV,GAMH ~ rad).

10. Magnitude of the velocity vector wrt to the earth's surface
    (VT ~ ft/sec).

11. The north, east, and down components of the inertial velocity
    vector (VN,VEE,VD ~ ft/sec).

12. The north, east, and down components of the velocity vector
    wrt the wind (VNR,VER,VDR ~ ft/sec).

13. The equivalent airspeed (VEQ ~ kt) and true airspeed (VKW ~ ft/sec).

14. The weight and mass of the aircraft (WAIT ~ lb; XMASS ~ slugs).

15. The coefficients of moments of inertia (XMC(1,2,5,6,8,9) ~
    non-dimensional, XMC(3,4,7,10) ~ $\text{slug}^{-1} - \text{ft}^{-2}$).

16. The coefficients of angular momentum of rotating machinery
    (XMCC1 to XMCC7 ~ sec^{-1}).

Special Features:

1. Initialize for the pilot station or c.g. (ICG=0 or 1). If ICG=0 then HIC, XIC, and YIC specify the initial coordinates of the pilot station wrt the runway axis system. The coordinates of the c.g. are calculated. If ICG=1 then HIC, XIC, and YIC specify the coordinates of the aircraft c.g. The coordinates of the pilot are calculated.

2. Specifying initial Euler angle rates instead of body axis rates (IEULR=1). If IEULR=1 then RBIC, QBIC, and PBIC are the initial values of $\dot{\psi}$, $\dot{\theta}$, and $\dot{\phi}$, respectively. The body axis rates are then computed.

3. Specifying the aircraft velocity (MACH = -1, 0, or +1). If IMACH = -1 then the variable VEQIC is the initial Mach number. If IMACH = 0 (default) then VEQIC is the initial equivalent airspeed (kt). If IMACH = +1 then the initial airspeed is specified via the body axis components of the aircraft velocity wrt the wind (UBIC,VBIC,WBIC ~ ft/sec).

4. If the aircraft is on the ground (IHIT=1) and IMACH $\geq$ 0, then VEQIC is the ground speed (i.e., taxi speed, kt).

2.2.2.3 RESEARCHER SUPPLIED SUBROUTINES

The researcher is required to supply mathematical models of the aerodynamics, control system, propulsion system, landing gear, wind, and turbulence. These models are then implemented in the subroutines AERO2, AERO3; CONTR2, CONTR3; ENGINE; GEARS; and WINDC.

The outputs of AERO2 and AERO3 must include the aircraft body axis components of the forces and moments due to aerodynamic loads (FAX,FAY,FAZ; TAL,TAM,TAN).

There are no required outputs from CONTR2 and CONTR3, but the outputs normally include control surface deflections required by the aerodynamics model.

The required outputs from ENGINE are the aircraft body axis components of the forces and moments due to the propulsion system (FEX,FEY,FEZ;TEL, TEM,TEN) and signals to drive the engine instruments in the cab. Note that the ENGINE subroutine is normally in the third loop (longest frame time). If this presents a problem, it should be moved to the second loop.

The required outputs of the GEARS subroutine are the normal, drag, and side forces due to each landing gear. Forces due to a tail strike can also be included.

The higher frequency components of the aerodynamics and control system models are implemented in AERO2 and CONTR2, and the lower frequency components in AERO3 and CONTR3. However, the researcher should be wary of separating aerodynamic forces and moments into AERO3 and AERO2, respectively, as some anomalies result. For example, a step elevator input would produce a pitching moment prior to the force that was responsible for the pitching moment. To avoid such anomalies it is recommended that all forces and moments be implemented in AERO2. This is also consistent with the calculation of angles of attack and sideslip in the second loop. AERO3 should be used to model such things as aerodynamic coefficients which are functions of flap setting or Mach number.

The subroutine WINDC is used to implement models of the wind and random turbulence. The required outputs are the local axis components of the wind and the components of the random turbulence. The turbulence components can be in local or body axes. The random turbulence can be modeled via the BWIND subroutine, as described in Section 2.2.2.4. When BWIND is used, WINDC must compute the RMS levels and scale lengths for the three linear components.

Special purpose features are implemented in the subroutines UTIL2, UTIL3, or SETUP. UTIL2 and UTIL3 are used to implement features required to be in the realtime loop, depending on frequency considerations. SETUP is used to implement features that only need to be in the IC loop. For example, UTIL2 could be used to implement the dynamic check routine (see the BDCHK5 subroutine described in Section 2.2.4), and SETUP could be used to implement the trim subroutine (see BQUIET subroutine described in Section 2.2.4).

The only other requirement of the researcher is to assign initial conditions. These include aircraft weight, inertias, geometry, position, velocity, and orientation. BASIC will assign default values to all variables not specified by the researcher. A good way to insure that all parameters have been properly set and the desired BASIC options selected is to use Tables B-1 and B-2 of Appendix B as checklists.

2.2.2.4 COMMONLY USED OPTIONAL SUBROUTINES

Succinct descriptions of optional but commonly used subroutines are contained in this section. These subroutines are useful in a wide variety of simulations and can be easily integrated into any particular model.

Atmospheric Turbulence. The MIL-F-8785B (Reference 2) model of atmospheric turbulence is implemented in a subroutine called BWIND. Program inputs are the aircraft velocity wrt the air mass (VRW), the "scale lengths" (UAL,WAL,VAL), and the RMS gust levels (UDISP,WDISP,VDISP). Program outputs are the linear and angular gust velocities in body axes (UTURB,WTURB,VTURB, PTURB,QTURB,RTURB). Detailed documentation can be found in Reference 3.

Linear Interpolation. Many times aircraft data is presented in tabular form. For example, the aerodynamic lift coefficient, C_L, might be tabulated as a function of angle of attack, α, and flap angle, δ_f. For such cases a continuous function of C_L versus α and δ_f can be obtained via linear interpolation. This capability is provided by the Function Generation System subroutines. Complete documentation of these subroutines is contained in Reference 6. Briefly,

SUBROUTINE	PURPOSE
THRUPUT	Specify the dependent and independent variables. Maximum of three independent variables.
VARBPT	Specify the values of the independent variables.
POINTS	Specify the values of the dependent variables.
VBARG	Calculate the coefficients of linear interpolation. Must be called for each independent variable.

SUBROUTINE	PURPOSE
FIXGN1	Performs the linear interpolation when there is only one independent variable.
FIXGN2	Performs the linear interpolation when there are two independent variables.
FIXGN3	Performs the linear interpolation when there are three independent variables.

Data Initialization. It is sometimes desirable to initialize many variables in one subroutine, rather than spread them among many subroutines. This is accomplished with the BLOCK subroutine. This is a non-executable subroutine and hence cannot contain any executable Fortran statements. It should contain only Common, Equivalence, and Data Statements.

Note that data initialization can also be accomplished via a CASPRE setup deck.

Realization of S-Plane Transfer Functions. There are a wide variety of techniques for obtaining a digital representation of a continuous transfer function. One technique is to use the z-transform. This results in a z-plane transfer function and the coefficients can be used in the required difference equation. There are two programs that perform the above operations. They are called FACT and UPDATE and are briefly described below.

FACT

    Called in IC loop only (exception: slowly-varying coefficients). Input is the s-plane transfer function. Outputs are the difference equation coefficients.

UPDATE

    Utilizing the buffer created by FACT, this routine updates the state vector. Inputs are the difference equation coefficients (buffer) and the transfer function input. Output is the transfer function output state vector. The user must form his particular "output" equation from the states.

2.2.3 DATA ACQUISITION ROUTINES

This section describes routines commonly used for the collection and output of data. Only brief summaries are included here. Whenever possible reference is made to more detailed documentation.

Magnetic Tape Data, BRUNDM. The researcher can store realtime data on 9-track, 800 BPI magnetic tape by using the subroutine BRUNDM. The subroutine uses a buffering technique to perform the tape output, and hence uses very little execution time. Also, there are virtually no restrictions on the number of variables or which variables can be stored. The how-to-use documentation is contained in Reference 4.

The output of the BRUNDM subroutine is in a standard format known as MAC/RAN. There are a number of stand-alone programs that can be used to analyze the contents of MAC/RAN tapes. Some of the more common ones are:

TAPETEST:

> Tests tape for format and content. Output includes
> maximum, minimum, mean, RMS, and standard deviation
> of each variable recorded.

MACPRINT:

> Prints out selected data to the line printer. Data
> can be selected by file number, variable name, and time.

BSTRIP:

> Provides strip chart type time histories on the Versatec
> printer/plotter.

XPLOT:

> Crossplots of selected variables within a specified
> file. Any variable can be used as the independent variable.

MAC/RAN:

Spectral and time series analysis.

SIXTAPES:

Converts a Sigma-7/8 generated MAC/RAN tape to
IBM-360 compatible MAC/RAN tape.

MACFIX:

Tape copy program which corrects MAC/RAN formulated
tapes which were improperly written. Also provides
the ability to correct EAI-8400 RUNDUM tapes to
Sigma format.

Histograms, HIST. Histograms of data collected during the realtime
mode (and saved in arrays) can be plotted on the digital printer/plotter
by using the subroutine HIST. Detailed documentation is contained in
Reference 7.

Digital Plots, VPLOT. Plots of data collected during the realtime
mode (and stored in arrays) can be plotted on the digital printer/plotter
by using the subroutine VPLOT. Detailed documentation is contained in
Reference 8.

Background Print, BGPRNT. There are a series of programs that enable
the Foreground user (i.e., the realtime simulation user) to use the Back-
ground printer (i.e., the high-speed line printer). This is done by
writing data on the disk, and later submitting a Background job to read the
disk file and print the data on the high-speed line printer. It has been
found that using this technique to print data can significantly reduce the
time between runs. At present there is no detailed documentation on the
Background print software.

Runlog Documentation, RUNLOG. This collection of software allows the
researcher to automatically document parameter values used in his simula-
tion. The way it works is as follows: the researcher specifies a set of
variables that he expects to vary during the course of his simulation

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(e.g., aircraft weight, control system gains, etc.). At the beginning of each simulation session <u>all</u> of these variables are printed. Thereafter, only the variables whose values have been changed are printed. This is done for each run and hence provides a "run log" of the program variables used throughout the simulation.

At present there is no documentation but the name of the primary subroutine is RUNLOG.

2.2.4 COMMONLY USED UTILITY ROUTINES

This section describes routines that are useful in a wide variety of simulations. As in Section 2.2.3, only brief summaries are included here, and detailed documentation is referenced.

<u>Trim Routine, BQUIET</u>. The subroutine BQUIET provides the capability for trimming the aircraft about all six axes. BQUIET was specifically designed to be used in conjunction with BASIC, and it is completely compatible with same. The outstanding features of BQUIET are discussed below. Detailed documentation can be found in Reference 9.

Program inputs are the number of controls, which variables are to be used as controls (e.g., pitch attitude, elevator, throttles, etc.), the maximum and minimum value of each control, and the aircraft flight condition (e.g., speed, flight path angle, etc.). Program outputs are the aircraft states at the specified flight condition.

Execution of BQUIET is initiated by setting the BASIC variable ITRMCM to one (ITRMCM is normally zero). BQUIET then sets the BASIC variables ITRIM and ITPROG to one (both are nominally zero), and proceeds to trim the aircraft. The variable ITRIM=1 has the effect of turning off the ADC's. (This is done so that the aircraft controls will not be read from the cab.) The variable ITPROG is used to signify the status of the trim (i.e., the "trim progress"). The aircraft is trimmed by perturbing the specified controls until the aircraft accelerations with respect to inertial space meet preset error criteria. The default value of these error criteria are

0.0005 rad/sec^2 for the angular accelerations, and 0.01 ft/sec^2 for the linear accelerations. After the error criteria are satisfied, the variable ITPROG is set to zero. Normal program execution is resumed by setting ITRMCM to zero. (Note that the trim algorithm will continue, even though ITPROG is zero, until ITRMCM is set to zero.) The variables ITRMCM and ITPROG are usually assigned to a DI and DO, respectively.

BQUIET is normally used to trim just the longitudinal axis. That is, wings level and the aircraft's heading calculated such that there is zero sideslip (i.e., calculate $\gamma_{H_{IC}}$ such that β is zero). When BQUIET is used in this manner only three independent controls are sufficient to obtain a unique trim solution. For example, pitch attitude, elevator, and throttle could be specified as controls, and speed, vertical flight path angle, and aircraft configuration (i.e., weight, flaps, etc.) could be used to specify the flight condition.

IC Print Routine, BICPRINT. The subroutine BICPRINT prints IC or trim conditions on the Foreground line printer. The output format is arranged such that the researcher can specify up to nine variables to be printed. In addition, sixty variables are taken from the BASIC common list XFLOAT. Complete documentation of BICPRINT is contained in Reference 10.

Dynamic Checks, BDCHK5. The subroutine BDCHK5 will produce dynamic checks for a wide range of inputs (e.g., impulse, step, doublet, saw tooth, sine wave). The researcher specifies the forcing function (e.g., throttles, column, etc.) and the type of input. Output can be recorded on the strip chart recorder and/or magnetic tape. Detailed documentation is contained in Reference 11.

Stability Derivatives, STABLE. Partial derivatives of a specified set of dependent variables with respect to a specified set of independent variables can be obtained with the subroutine STABLE. The researcher specifies the dependent variables (e.g., total forces and moments), the independent variables (e.g., throttles, column, etc.), and the step sizes of the independent variables. STABLE calculates the values of all stability derivatives and prints them on the Foreground line printer. Complete documentation of STABLE is contained in Reference 12.

Random Numbers, XNORM. The subroutine XNORM generates random numbers with a Gaussian distribution. Documentation is contained in Reference 13.

Plots of Function Table Data, FTD. The subroutine FTD will generate tables and/or plots of the Function Table Data used by the linear interpolation subroutines (see description in Section 2.2.2.4). This provides a convenient means of documenting data used in the simulation model. A complete description of FTD can be found in Reference 14.

Print a Message, TYPEOUT. Messages can be printed on the Foreground terminal (i.e., the CRT described in Section 2.1.3) via the subroutine TYPEOUT. This feature has proven useful when used in conjunction with the Background print feature. For example, a few key end-of-run parameters can be printed on the CRT (e.g., touchdown rate of sink), and the bulk of the end-of-run data can be printed on the high-speed line printer. Complete documentation of TYPEOUT can be found in Reference 15.

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II-9   McFarland, Richard E., BQUIET, A Six-Degrees-of-Freedom Trim Process
        Fully Integrated into the BASIC System, NASO 72-12, November 1972.

II-10   Astill, D. L., BICPRINT, NAPS-122, April 1972.

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II-12   Alderete, T. S., STABLE, NAPS-149, July 1973.

II-13   Shirley, R. and J. Mauer, <u>XNORM</u>, NAPS-89, November 1973.

II-14   Saito, J., <u>FTD (Function Table Display)</u>, NAPS-130, June 1972.

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(Updated), February 1974.

SECTION 3

COCKPIT

3.1 GENERAL DESCRIPTION

3.1.1 GENERAL LAYOUT WITH DIMENSIONS

The cab of the FSAA is configured generally as a transport flight
deck. Within the spacious cockpit are mounted 747 flight deck seats for
pilot and copilot. The cockpit is large enough to accommodate other seats
and panels, if required, and generally a third observer's seat is installed.
The cab has an instrument panel and front, center, side, and overhead
consoles that can mount a variety of controls and instruments. The modular
construction of the cockpit allows the rapid mounting of mini-panels con-
taining clusters of standard instrument groups. A mini-panel, however,
may be made that houses a special-purpose display or control device.

Two collimating lens assemblies are mounted in place of forward-looking
windows before the pilot and copilot. The view through one of these lenses
is that of two cathode-ray tube (CRT) faces, one from direct viewing, the
other from a beamsplitter. The outside visual scene is displayed on the
directly-viewed color-television monitor, the head-up display (HUD) on the
CRT viewed by means of the beamsplitter. The other side of the cab has a
view of only the outside scene. The beamsplitter and HUD assembly may be
mounted before either seat.

The basic cockpit controls are conventional column, wheel, and
rudder pedals. The center console can contain a variety of power and
subsystem controls. Many types of mini-consoles are available for flight
control system manipulation and for operation of flaps, gear, nacelles,
wings, and other surfaces. A typical configuration is shown in Figure 3.1.1-1.

Some approximate dimensions of interest to the researcher are given
below. The interior of the cockpit is roughly cylindrical with a diameter

Figure 3.1.1-1: A Typical Cockpit Configuration

of 215.9 cm (85 inches). The length from the front console to the rear wall is 208.3 cm (82 inches). The pilot and copilot seats (back surfaces) are normally 83.8 cm (33 inches) aft of the front panel with an adjustment from 68.6 cm (27 inches) to 91.4 cm (36 inches). The cockpit height at the seat back surface, seat center is 149.9 cm (59 inches). The seats are 114.3 cm (45 inches) apart (center to center) and the vertical adjustment gives a clearance to the ceiling of the top of the back rest a range of 48.3 to 63.5 cm (19 to 25 inches). The motion system gimbal center is located between the seats, 45.7 cm (18 inches) above the floor and 83.8 cm (33 inches) aft of the front panel surface. These dimensions are clarified in Figure 3.1.1-2.

The design of the cab emphasizes flexibility so it is possible to change the configuration to include special display devices, seats, and control manipulators. A major changeover from one configuration to another requires about one week.

The maximum allowable number of persons in the cockpit during operations is three. Communication with simulator/computer operators and test directors is facilitated by speaker/headset/microphone units. Speakers are mounted in the cockpit for sound simulation and the lighting is adjustable by the pilot and copilot.

The center console generally has a complete set of mode control buttons (IC, HOLD, and OPERATE). An IC (RESET) button is generally also provided on the pilot's wheel or stick. The computer can be put into OPERATE from the cab only if the motion drive is disabled.

3.1.2 SOME TYPICAL COCKPIT CONFIGURATIONS

Three cockpit layouts are shown in Figures 3.1.2-1, 3.1.2-2, and 3.1.2-3. They show the panel layouts for the XV-15 Tilt Rotor Research Aircraft, the Space Shuttle, and the USAF KC-135. Note that the primary differences between the three are the center manipulator used in the Space Shuttle, the left-hand collective/power lever used in the XV-15 research aircraft, and the conventional wheel for the KC-135. Note also

CEILING TO BACK REST CLEARANCE ADJUSTABLE FROM 48.3 CM (19 IN) TO 63.5 CM (25 IN)

215.9 CM (85 IN)

208.3 CM (82 IN)

114.3 CM (45 IN)

45.7 CM (18 IN)

149.9 CM (59 IN)

GIMBAL CENTER IS 83.8 CM (33 IN) AFT OF FRONT CONSOLE AND 45.7 CM (18 IN) ABOVE FLOOR

NORMALLY 83.8 CM (33 IN) ADJUSTABLE FROM 68.6 CM (27 IN) TO 91.4 CM (36 IN)
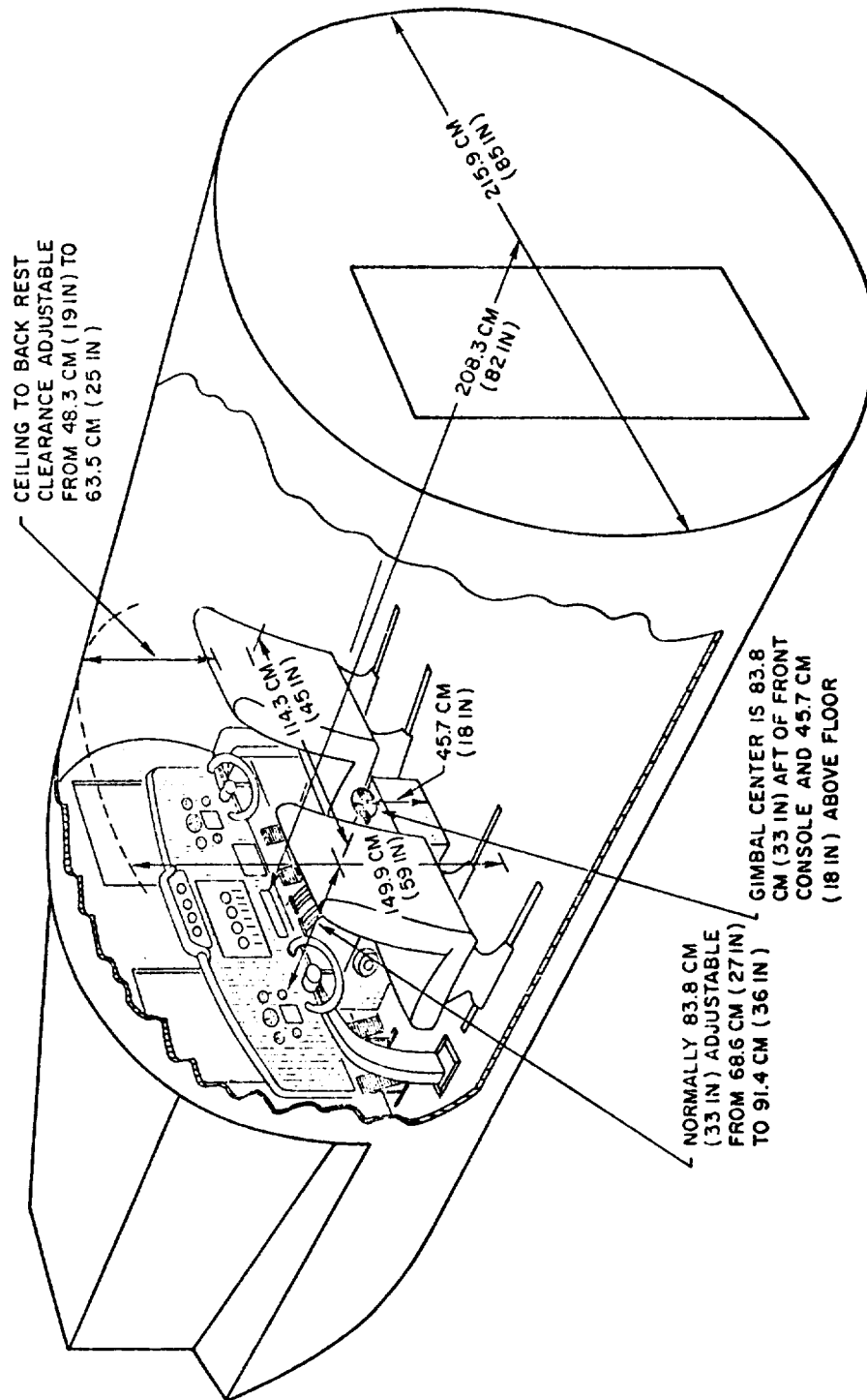
Figure 3.1.1-2:   Typical Cockpit Dimensions
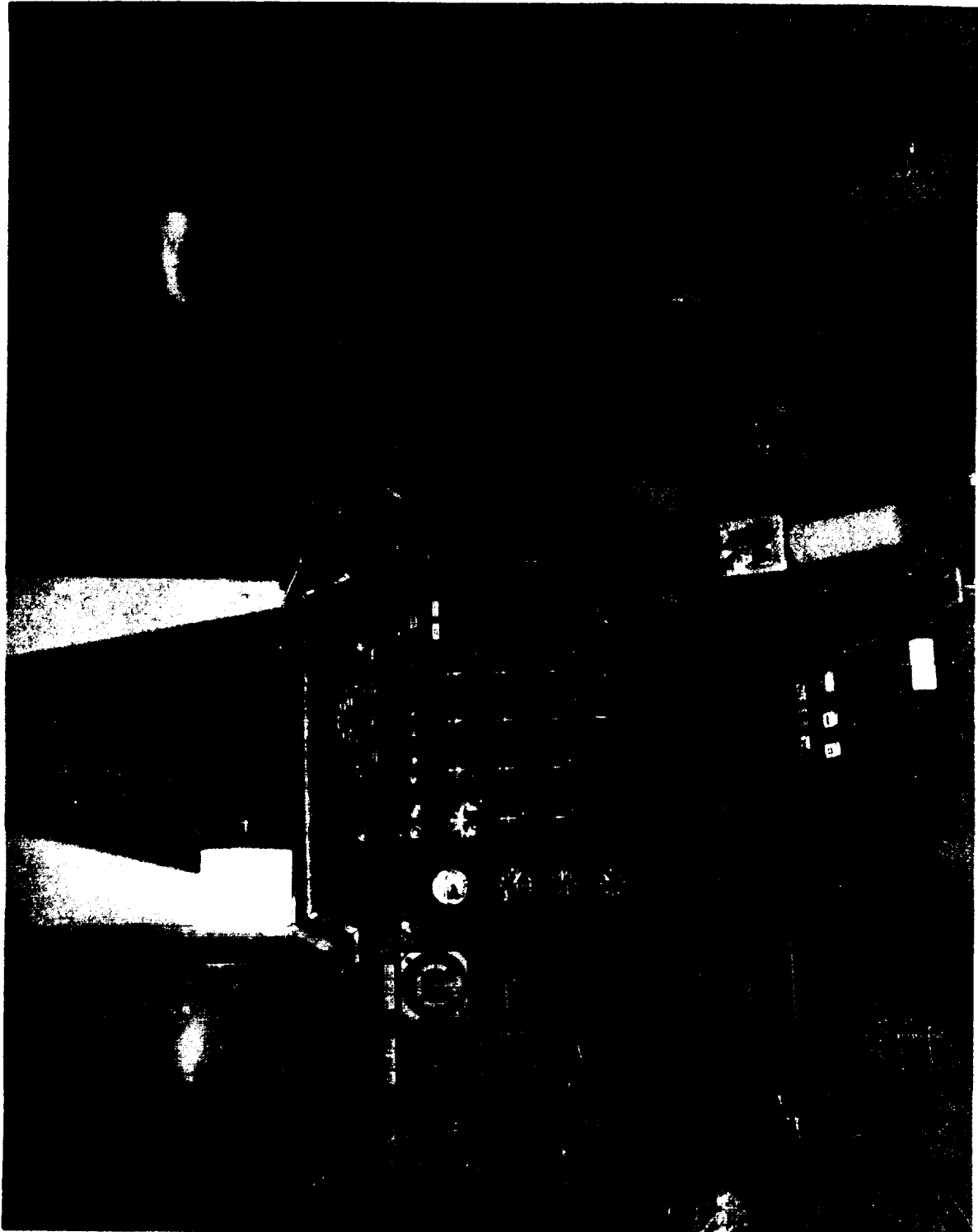
Figure 3.1.2-1: XV-15 Tilt Rotor Research Aircraft Cockpit Layout
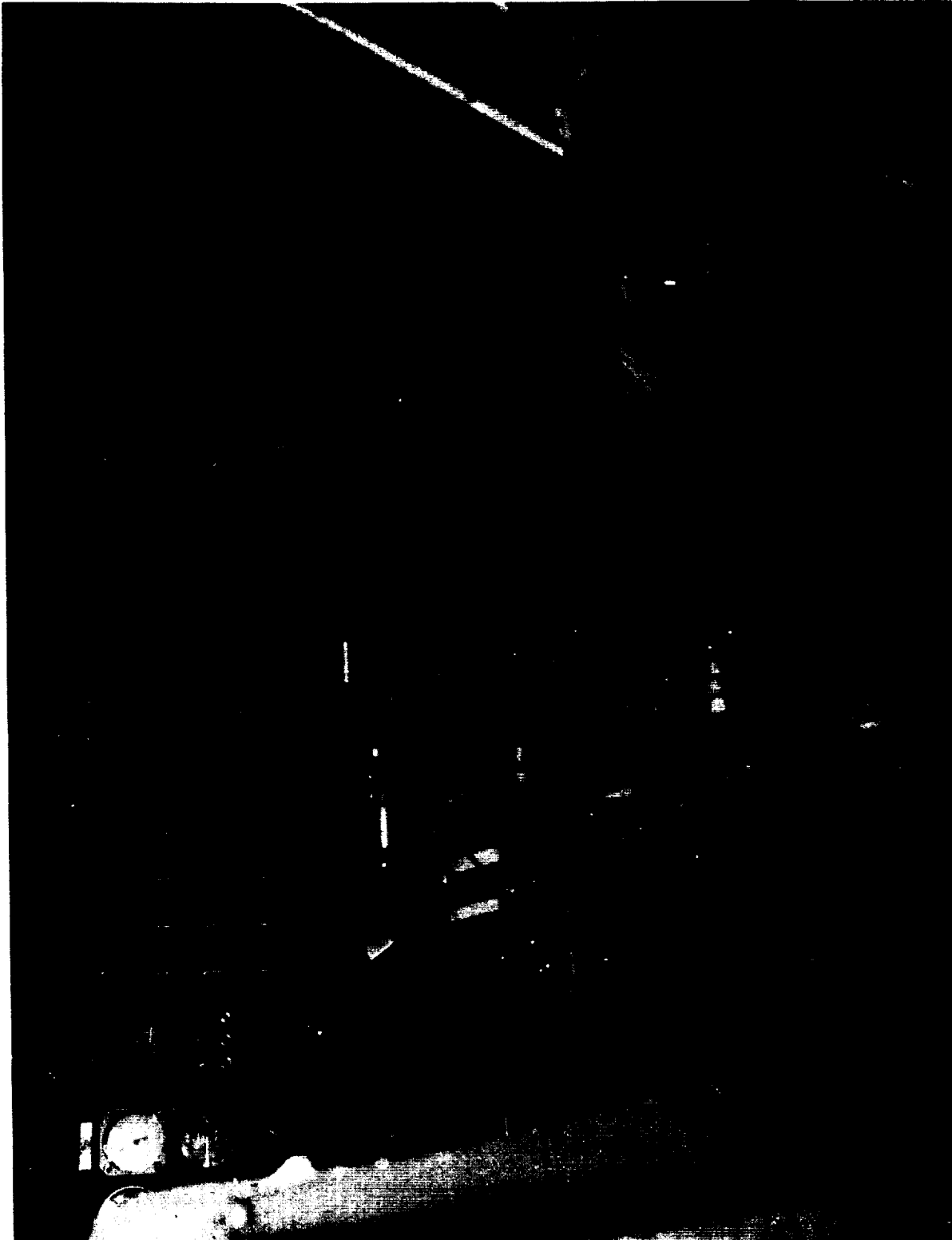
Figure 3.1.2-2: Space Shuttle Cockpit Layout
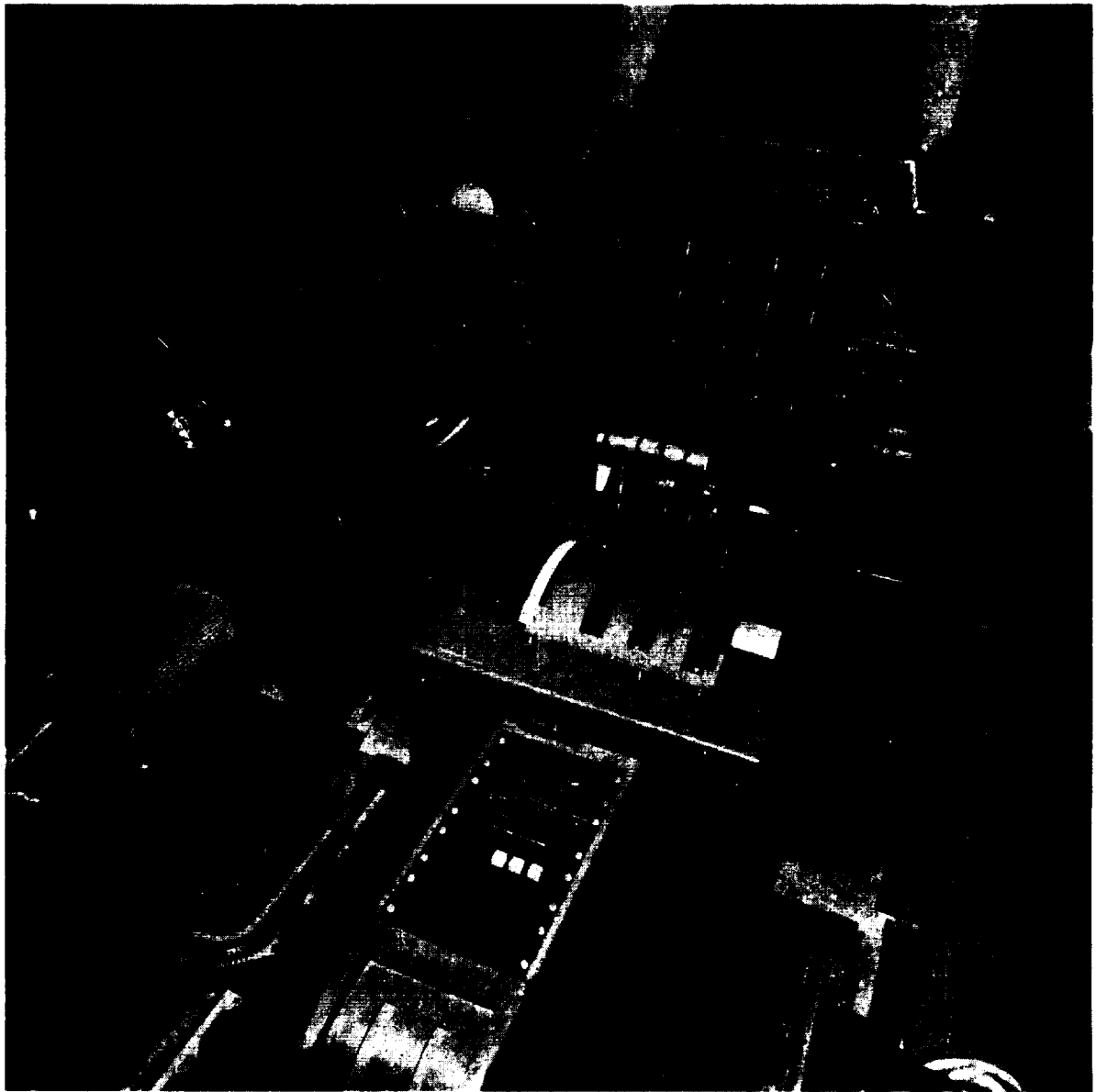
Figure 3.1.2-3: USAF KC-135 Cockpit Layout

the variety and location of control system panels. The right seat of the XV-15 aircraft is the primary pilot's seat, which is the case for most rotorcraft. This facilitated installation of the collective/power lever in the center console.

3.2 INSTRUMENTS

3.2.1 AVAILABLE INSTRUMENTS

By modifying standard voltmeter faces and the use of commercially-available instruments designed expressly for flight simulators, a wide variety of instruments are available for use in the FSAA. A list of the more familiar ones follows:

1) <u>Attitude-Position</u>

   Attitude direct indicator with cross bars
      and turn unit (2 axis and 3 axis)

   Horizontal situation indicator

   Radio altimeter

   Barometric altimeter

   Gyro compass

2) <u>Speed</u>

   Rate-of-climb indicator

   Instantaneous vertical speed

   Indicated airspeed

   Machmeter

3) <u>Power Plant</u>

   Fuel flow

   Fuel quantity

Engine pressure ratio

Exhaust gas temperature

Engine % RPM

Rotor speed

Transmission torque

4) Acceleration/Rates

Normal acceleration

Turn and slip

5) Air Mass Angles

Angles of attack

Sideslip

6) Configuration

Center-of-gravity indicator

Flap position indicator

Nacelle position indicator

Trim indicator

Surface position indicator

Speed brake position indicator

Landing gear position indicator

Multiple trim indicator

The basic instrument units are 7.62 cm (3 inches) in diameter, the engine/configuration indicators are 5.08 cm (2 inches) in diameter. In general, attitude-direction and horizontal situation indicators are synchro-drive units. Most of the other indicators are DC servo type. Special purpose instruments may be made to the researcher's specifications.

3.2.2 INSTRUMENT CHECKOUT

Since there are 450 trunk lines available from the central computer
to the cab for purposes of driving instruments, etc., it is advisable to
check continuity. A static check is available as a standard subroutine
of BASIC to accomplish this daily. Since there are no instrument feedbacks
to the computer, verification must be accomplished visually as part of the
morning set-up procedure.

When it is desired to point the simulated aircraft to either the
zenith or nadir for any reason, the attitude ball may not behave like a
real flight instrument. The reason for this is that the real instrument is
a gyro device whereas the simulated instrument is a synchro-device that is
driven by Euler angles generated in the BASIC routines. These angles are
not defined uniquely at the zenith and nadir and, consequently, the behavior
of the instrument may be erratic following operation where the aircraft is
so pointed.

3.3 HEAD-UP DISPLAY

3.3.1 OPTICAL CHARACTERISTICS

The image for the head-up display (HUD) is generated by a graphics
display computer and displayed on a cathode ray tube. This image is reformed
at optical infinity by two plano-convex lenses mounted before the pilot or
copilot. A 45 deg beamsplitter oriented at 45 deg between the lens and
monitors permits the pilot to view the HUD and the outside visual scene
display simultaneously. The actual HUD CRT is mounted above the cockpit
and its optical axis is at 90 deg to the line of sight. A schematic view
of the lenses and beamsplitter is shown in Figure 3.3.1-1. Brightness,
gain, and centering controls are located above the cockpit and can only be
adjusted when the cockpit is docked. The apparent brightness range of the
HUD is sufficiently high so that its superimposed image is highly visible
on the outside scene. The quality area of the 53.3 cm (21 inch diagonal
measure) CRT is 25.4 x 25.4 cm (10 x 10 inches). The useful area is

HUD CRT

Direct-View CRT

53.3 cm (21 in.)

61.0 cm (24 in.)

Beamsplitter

Plano-Convex Lenses

Eye Reference Point
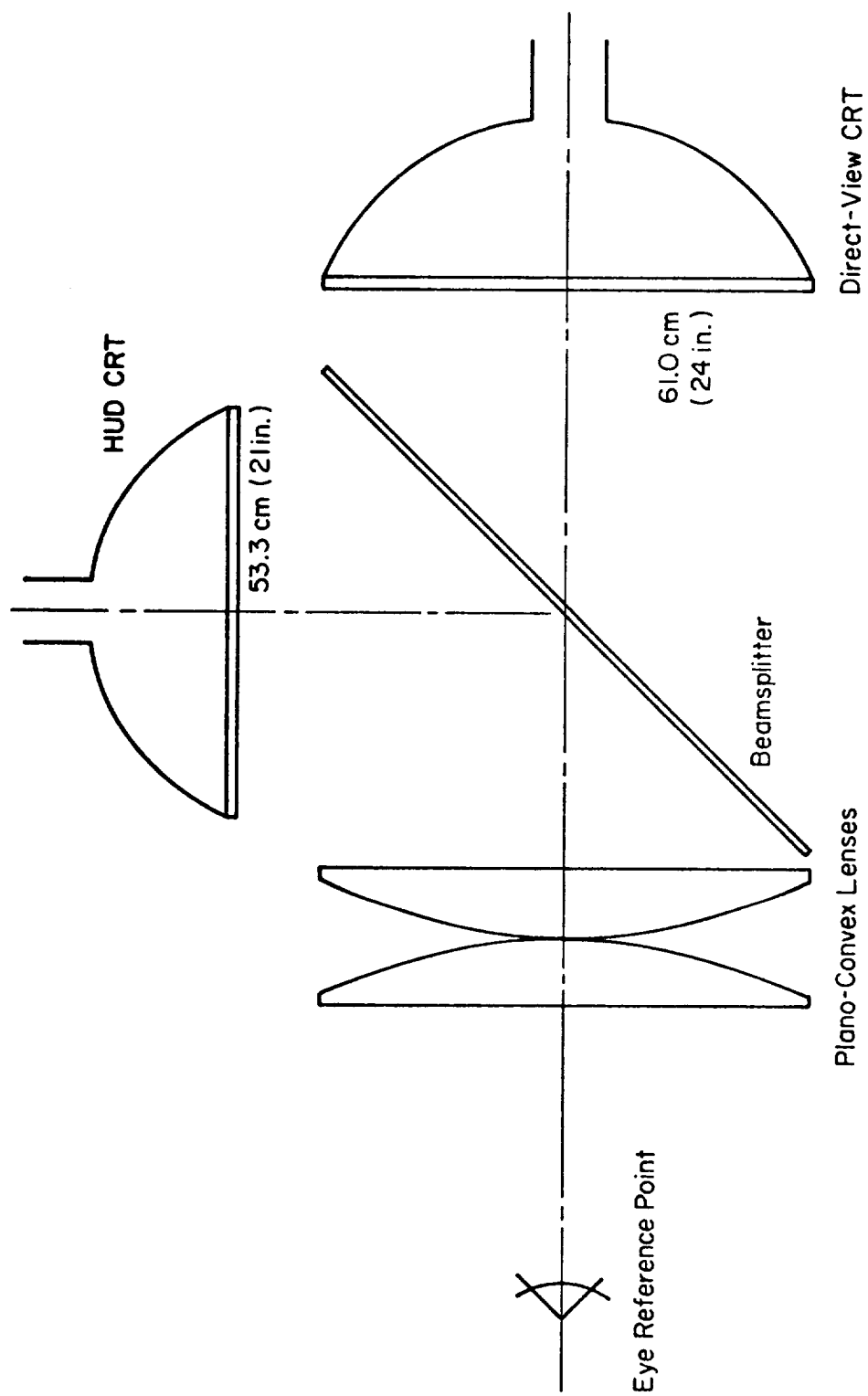
Figure 3.3.1-1: Schematic View of the HUD Lenses and Beamsplitter

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27.9 x 27.9 (11 x 11 inches). At the pilot's seat, these dimensions subtend angles of approximately 13 deg horizontally and 13 deg vertically.

The angular magnification factor of the plano-convex viewing lenses is two, therefore the HUD field of view is about 26 by 26 degrees. A slight "pincushion" distortion is apparent and is documented in Section 4.4. A schematic view of the lenses and beamsplitter is shown in Figure 3.3.1-1.

3.2.2   LINE DRAWING CAPABILITY

The line generating unit of the HUD is an Evans & Sutherland Picture System. This is a sophisticated computer graphics system capable of drawing lines and characters. It consists of a Digital Equipment Corporation PDP-11/40 mini-computer, a picture processor, a refresh buffer unit, a character generator, and a picture generator and display (CRT). When viewed functionally, the elements of the system are:

- A Picture Controller that contains the image data base, executes the display programs, and performs input-output operation. The computer is a PDP 11/40 with 16K core memory (16 bit word). It includes a dual DEC tape drive, a 1.2 Mbyte disk cartridge, and a paper tape punch/reader. Line drawing modes included in the Picture Controller are: move, beam moves and intensity is off; draw, beam moves and intensity is on; dot, beam moves to a new position, stops, and the intensity is switched on to form a dot; character draw, picture elements may be drawn using any of the above modes one by one or in sequence.

- A Picture Processor that translates, rotates, scales, clips, and creates mirror and perspective images of figures. It is implemented in associated digital hardware. In addition, the Picture Processor can perform transformation matrix multiplication while maintaining full-word accuracy. It can also generate perspective changes as large viewing angles are

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approached, and zoom. A memory write back capability is
included for generation of hard copies. The Picture Processor
frame update time is an integral multiple of the refresh
buffer cycle time.

● A Refresh Buffer that stores processed digital frame data
allowing complete separation of picture display refresh
requirements from the dynamic picture update requirements.
Buffering permits data to be transmitted when data flow
rates or timing between output and input points are difference.
Digital data is deposited in the buffer by either over-writing
the data for the previous picture in single buffer mode, or
in a separate area from the previous picture in double buffer
mode. The buffering mode is program selectable. In single
buffer mode, up to 8188 dots, line endpoints, or character
code entries can be stored in the buffer in any combination.
In double buffer mode, the total capacity is 4092 elements.
The refresh cycle is normally 25 msec long but, if the
refresh is not completed in this time, a second cycle is
required before the picture will be regenerated.

● A Character Generator that accepts character codes and
produces properly sized digital character stroking data
for the Picture Generator. The character set consists
of 96 different symbols. A maximum of 2000 characters
can be displayed flicker-free at a refresh rate of 30 frames
per second. There are 8 character sizes available under
program control ranging from 0.24 cm (3/32 inches) high in
increments of 0.24 cm (3/32 inches) to 1.91 cm (3/4 inches)
high on the Picture Display. The character width is also
under program control with 8 different widths selectable
for each size. Characters may be displayed in a 90 degree
counter-clockwise orientation.

● <u>A Vector Generator and Picture Display</u> that converts digital
coordinates and intensity information to analog voltages to
drive a cathode ray tube. Line modes include solid, blank,
and dash. Intensity ranges across 256 levels and may be
varied with a range coordinate for depth cueing. The contrast
control is independent of the intensity control. The spot
size is 0.5 mm (0.020 inches). There are 4096 x 4096 addressable
locations and endpoint matching is within 0.5 mm (0.020 inches).
The CRT size is 53.3 cm (21 inches) rectangular with a 25.4 x
25.4 cm (10 x 10 inch) quality viewing area.

The researcher must specify the line configuration of his head-up
display, the characters required, and their dynamic interaction with the
simulated aircraft. These may take the form of sketches, photographs,
computer printouts, or hard copies of other graphic displays.

3.3.3 TIMING CONSIDERATIONS

Studies by Queijo and Riley[*] have shown that time delay in the scene
presentation can have large effects on pilot performance depending on the
flying task of the simulation. Thus, it is important to understand the
relation between scene complexity and the time required by the computer
graphics system to process the scene. Generally, the fewer the number of
lines comprising a given scene, the less the processing time required to
generate it. However, the smallest processing time lag possible is the
period of the refresh rate which is typically the 25 msec used to eliminate
scene flicker. This minimum time would be appropriate for simple head-up
displays and flight directors.

Out-the-window scenes, such as landing fields, require many dots and
lines and therefore take more time to process. It is believed that update
rates of 16 frames per second are possible for relatively simple out-the-
window scenes using four colors and 2000 points in the scene. For this case
there would be a 60 msec lag in scene presentation.

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[*] Queijo, M.J., and Donald R. Riley, <u>Fixed-Base Simulator Study of the
Effect of Time Delays in Visual Cues on Pilot Tracking Performance</u>,
NASA TN D-8001, July 1975.

3.3.4 HUD CHECKOUT

The head-up display is essentially a collimated sophisticated computer graphics terminal whose image is placed before the viewer by means of a beamsplitter. The dedicated PDP-11/40 computer is linked to the central computer and receives airframe state information from it that controls the HUD image. The PDP-11/40 is synchronized with the central computer but its frame time may be different from that of the central computer. Care must be exercised to ensure that the PDP-11/40 frame time is not so large that the displayed data "jumps" are discernible. The refresh buffer will always control the display so that flicker is unnoticeable.

If the researcher can ascertain that the discrete aspects of the HUD image do not affect or enter in the dynamics of his problem, then a static check of the image is sufficient. This may be accomplished in the usual way (hand calculation, etc.) and verified by comparison with the hard copy. A visual inspection of the brightness qualities of the display may be necessary if the hard copy values of intensity variation are not accurate.

If the imagery to be presented is of a relative nature, i.e., movements are referenced to some point or line in the image itself, then the real apparent angular size of the image will not strongly influence the simulation (within reason, highly magnified or attenuated images will obviously cause problems) and the researcher need not concern himself with this question.

If, on the other hand, an absolute display is desired or reference to the outside scene is desired, then the apparent angular size of the HUD image presented to the pilots must be determined. This may be done by generating a known grid pattern on the CRT and measuring the angular size of the grid points with an angle-measuring instrument from the pilot's eye point (a nominal point between the eyes). If the distance from the CRT to the pilot's eye point and the magnification of the focusing lenses are known, the apparent size of the display may be calculated. The nominal value of the former is 121.9 cm (48 inches) and the magnification of a simple plano-convex doublet forming a magnifier is approximately two, if the virtual image is focused at infinity. This magnification will vary slightly

with angular distance off the axis and therefore can cause a noticeable amount of "pincushion" type distortion. A typical plot of the mapping of a CRT grid image into an apparent grid is shown in Figure 4.4.4-1.

The HUD may be checked against objects in the outside visual scene as generated by the VFA-07 display monitor. In this case, attitude information, for example, may be directly compared with the visual horizon. Existing features such as runways may be compared with earth-fixed elements of the HUD. Additional elements may be placed on the rigid model of the outside world to help facilitate checkout. When registration between the HUD and the outside scene is important, care must be exercised in assuring that monitor gains do not change. A daily registration check is recommended. Required adjustments are made in the centering and x-y gain parameters of the simulation program.

3.4 COCKPIT CONTROL LOADERS

3.4.1 GENERAL DESCRIPTION

A control loader system is mounted in the FSAA cockpit to provide control force feel simulation. The system consists of a three-axes set of cockpit controls (pedals and wheel/column or stick) with integral rotary hydraulic actuators, valves, and transducers. It also includes an associated console of servo control and function generating electronics. By interfacing these loaders with the central digital computer through an analog computer, it is possible to simulate a wide range of control force characteristics. These characteristics may be functions of control position, rate, and aircraft parameters such as airspeed and angle of attack. The system can simulate variable spring gradient, viscous friction (damping), breakout (preload), deadband (backlash), coulomb friction (hysteresis), and control travel limits. Stick or wheel/column trim is available through a trim button on the stick grip or wheel. Trim rate is variable.

A rate limiting feature is provided that limits the rate of force buildup. It is designed to prevent runaway operation or a response to inadvertent computer commands. The system resets when the limit is reached.

Two hydraulic rotary actuators are connected directly to the stick. The rotary actuator provides a more compact package than the typical linear actuator and also eliminates rattle caused by loose joints, a common problem in linearly actuated loaders. The actuators are supported on hydrostatic bearings to eliminate friction. In addition, the actuators are sealed by a vacuum return system, thus eliminating the need for seals with their attentive friction. Two standard servo valves are mounted on the roll actuator. Pitch is supplied by internal commutation of the oil ports. A differential pressure transducer is utilized as the force sensing element. A position transducer and tachometer provide the feedback position and velocity signals respectively. A similar setup is used with the wheel/column and rudder pedal controls. The important performance characteristics are listed in Table 3.4.1-1.

3.4.2 CONTROL LOADER OPERATION

An overview block diagram of the loader is shown in Figure 3.4.2-1. Each axis of the loader system is basically configured as a force servo. Valve position is controlled by the difference between a commanded force and the actuator force. The actuator force is the force applied to the system by the hydraulic actuator and is measured by a differential pressure transducer. The feedback compensation for this loop has been carefully designed to achieve a high loop bandwidth (> 10 Hz).

Because of this high bandwidth, the force felt by the pilot will closely approximate the force command. The force command is an electronically generated function of control displacement and rate. This command generation can be done either in the special loader electronics unit or an analog computer. However, the loader electronics can only simulate a fixed gradient and damping. For more complex feel system characteristics, or to provide variations with flight condition, it is necessary to use the analog computer.

TABLE 3.4.1-1

CONTROL LOADERS' CHARACTERISTICS

LOADER	WHEEL-COLUMN/PEDALS			STICK/PEDALS		
AXIS CHARACTERISTIC	WHEEL (17.8 cm RADIUS)	COLUMN	PEDALS	LONGITUDINAL	LATERAL	PEDALS
MAXIMUM CONTROL TRAVEL	± 105 deg	Typ. total travel ~ 35.6 cm (Mech. Stops)	± 8.3 cm	± 15.2 cm	± 15.2 cm	± 8.3 cm
MAXIMUM CONTROL FORCE OR TORQUE	75.1 m-Newton	± 667.2 Newton	± 889.6 Newton	± 978.6 Newton	± 400.3 Newton	± 480.4 Newton
THRESHOLD FORCE/TORQUE	15.82 cm-Newton	0.89 Newton	0.89 Newton	0.89 Newton	0.89 Newton	0.89 Newton
MAXIMUM CONTROL VELOCITY	± 340 deg/sec	± 127 cm/sec	± 127 cm/sec	± 127 cm/sec	± 127 cm/sec	± 127 cm/sec

TABLE 3.4.1-1

CONTROL LOADERS' CHARACTERISTICS

LOADER AXIS CHARACTERISTIC	WHEEL-COLUMN/PEDALS			STICK/PEDALS		
	WHEEL (7 inch RADIUS)	COLUMN	PEDALS	LONGITUDINAL	LATERAL	PEDALS
MAXIMUM CONTROL TRAVEL	± 105 deg	Typ. total travel ~14 in (Mech. Stops)	± 3.25 in	± 6 in	± 6 in	± 3.25 in
MAXIMUM CONTROL FORCE OR TORQUE	700 in-lb	± 150 lb	± 200 lb	± 220 lb	± 90 lb	± 108 lb
THRESHOLD FORCE/TORQUE	1.4 in-lb	0.2 lb	0.2 lb	0.2 lb	0.2 lb	0.2 lb
MAXIMUM CONTROL VELOCITY	± 350 deg/sec	± 30 in/sec	± 50 in/sec	± 30 in/sec	± 30 in/sec	± 30 in/sec
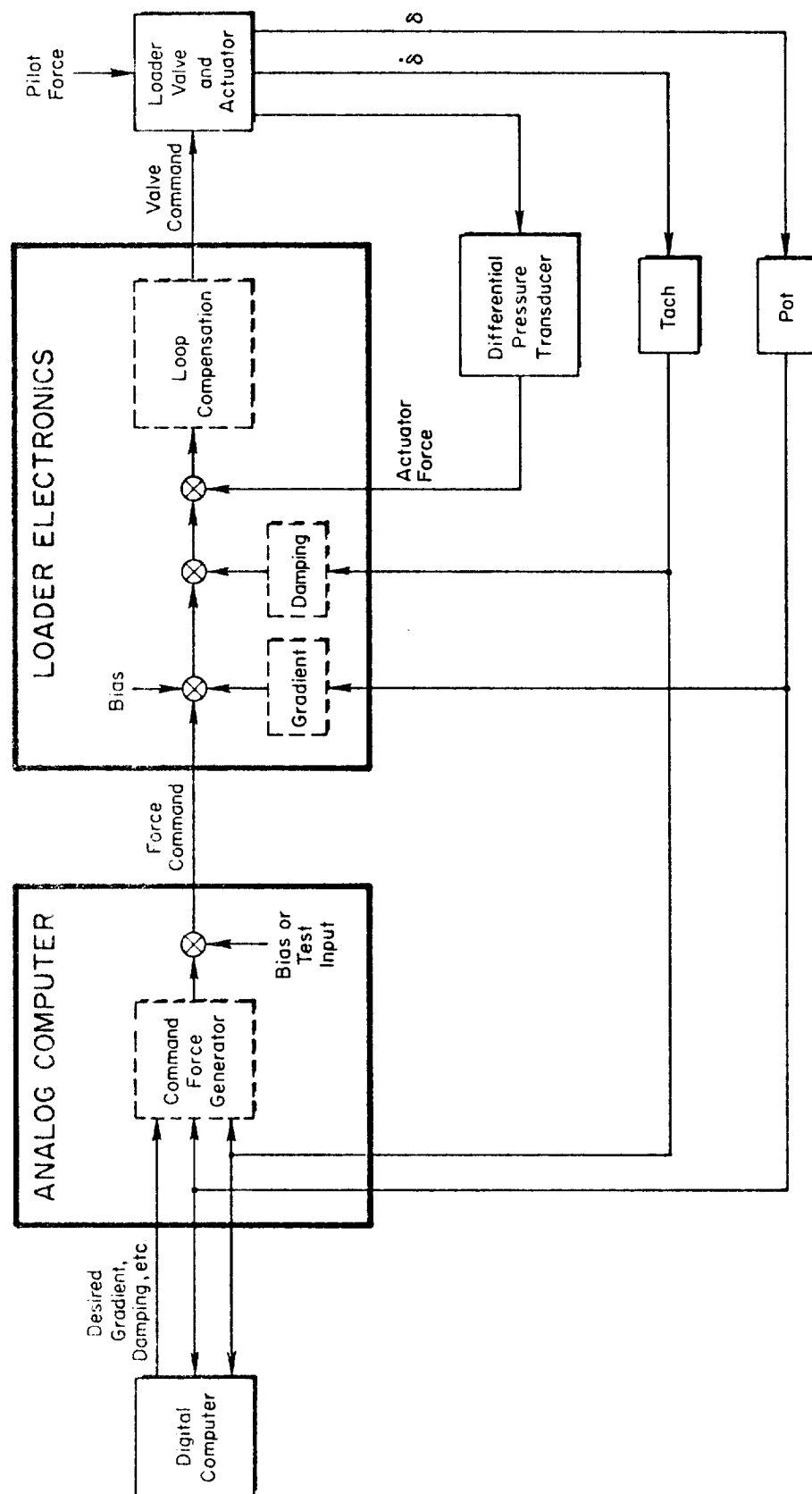
Figure 3.4.2-1: Overview Block Diagram of Cockpit Control Loader System

The force command is generated on an EAI 231R analog computer with inputs from the digital computer. The following parameters can be varied by the digital computer:

- Gradient
- Damping (viscous friction)
- Hysteresis (coulomb friction)
- Breakout (preload)
- Bias force
- Trim position
- Stops (position limits).

If any of the parameters listed in Table 3.4.1-1 do not vary, the constant values can be set external to the digital computer. On the other hand, desired variations with flight condition can be simulated by providing the appropriate computations in the digital computer.

One parameter which cannot be independently controlled is the effective loader mass. If the loader is set to simulate only gradient, K, and damping, B, terms, the dynamic response transfer function (control deflection/pilot force) is closely approximated by:

$$\frac{\delta}{F_P} = \frac{1}{m_e s^2 + Bs + K}$$

The effective mass, m_e, is not the physical mass of the system but is a complex function of the force loop, valve, and actuator characteristics. It is also a function of the gradient as illustrated in Table 3.4.2-1. In this table, apparent masses are presented for several gradient levels. The apparent masses were calculated from the gradient values and measurements of the frequencies where the phase angle is 90 deg. A typical frequency response plot obtained with a wave analyzer is shown in Figure 3.4.2-2.

TABLE 3.4.2-1

CONTROL LOADER EFFECTIVE MASS

Damping Ratio = 0.7

Masses derived from measured frequency
response data at 90 deg phase angle

LOADER/AXIS	WHEEL-COLUMN/PEDALS			STICK/PEDALS		
	WHEEL	COLUMN	PEDALS	LONGITUDINAL	LATERAL	PEDALS
GRADIENT	1.38 N/deg	8.06 N/cm	29.2 N/cm	3.5 N/cm	1.75 N/cm	8.76 N/cm
MASS	0.041 kg-m²	7.08 kg	5.4 kg	3.45 kg	1.36 kg	4.2 kg
GRADIENT	5.52 N/deg	20.31 N/cm	116.8 N/cm	10.5 N/cm	3.5 N/cm	28.9 N/cm
MASS	0.028 kg-m²	6.17 kg	4.2 kg	2.9 kg	1.3 kg	4.2 kg
		32.40 N/cm				
		5.13 kg				

TABLE 3.4.2-1

CONTROL LOADER EFFECTIVE MASS

Damping Ratio = 0.7

Masses derived from measured frequency
response data at 90 deg phase angle

LOADER/AXIS	WHEEL-COLUMN/PEDALS			STICK/PEDALS		
	WHEEL	COLUMN	PEDALS	LONGITUDINAL	LATERAL	PEDALS
GRADIENT	0.31 lb/deg	4.6 lb/in	16.7 lb/in	2 lb/in	1 lb/in	5 lb/in
	0.03 slug-ft^2	15.6 lb	11.9 lb	7.6 lb	3.0 lb	9.2 lb
MASS	1.24 lb/deg	11.6 lb/in	66.7 lb/in	6 lb/in	2 lb/in	16.5 lb/in
	0.021 slug-ft^2	13.6 lb	9.2 lb	6.5 lb	2.9 lb	9.2 lb .
	18.5 lb/in					
	11.3 lb					
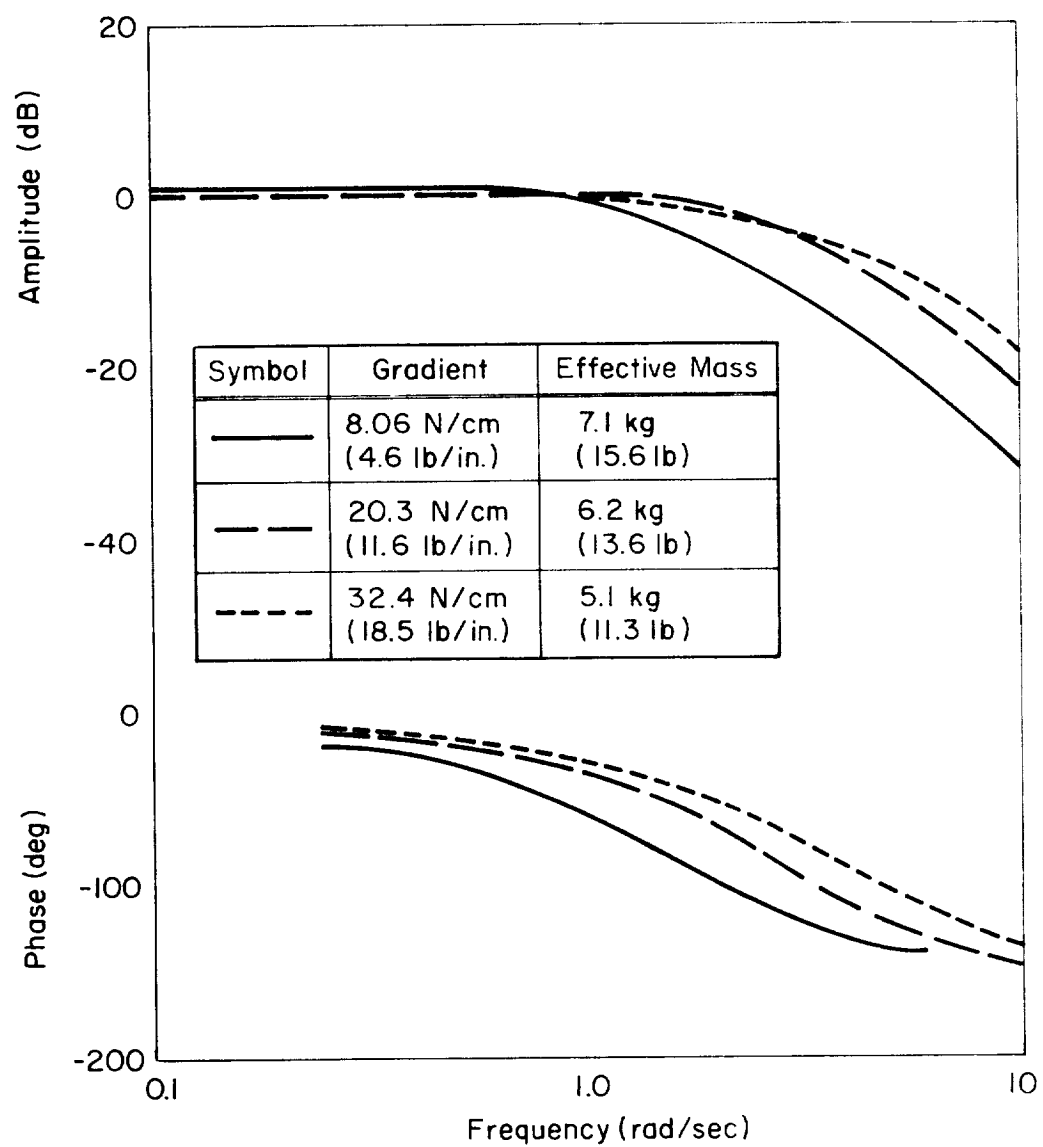
Figure 3.4.2-2: Measured Frequency Response for the Column
Simulating a Second Order System with 0.7 Damping Ratio

3.5 SOUND SYSTEM

3.5.1 GENERAL DESCRIPTION

The sound generator of the FSAA is a commercially made device designed
for use in transport training devices. It is driven by and therefore
interfaced to the central computer. Choice of its functions is made by
setting the appropriate controls on its console. Individual volume control
of the two cockpit speakers is accomplished by two knobs on the left-hand
console in the cockpit.

The components of sound generated by this device are:

- Noise generated by air flowing past the aircraft.

- Turbojet engine compressor whine and exhaust
  rumble from four engines.

- Noise from the air conditioning system.

- Turboprop engine propeller "slap" and compressor
  whine from four engines.

- Thrust reverser sound.

- Landing gear actuation sound.

- Runway rumble noise.

The sum of the sound from all these components is summed within the
generator. Individual volume and speaker balance controls on the console
may be used together with the pilot controls in the cockpit to adjust
the sound subjectively.

3.5.2 REQUIRED INPUTS

Sound generators of this type contain white noise sources that are
filtered so that their application to a loudspeaker produces a definite
identifiable sound, such as jet engine "rumble". Many aircraft sounds
are comprised of band-limited white noise and this is not an unreasonable

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view considering the processes that cause these sounds. Generally these are vortices (pressure disturbances) associated with a shape passing through air.

In the case of rotor noise, this is accomplished simply by modulating filtered white noise by a square wave, and applying the result to a high fidelity speaker. Varying the square wave frequency gives the aural sensation of varying rotor speed, and varying the amplitude of the square wave produces an effect similar to that of varying rotor thrust. By increasing the square wave frequency even further, sounds quite similar to automobile engine sounds and outboard motors are produced.

By adjusting the white noise filter to pass higher frequencies, compressor whine may be created. Varying the center frequency of this filter will create the impression of varying compressor speed.

A "clacker" device has been used to indicate engine failure. The sound produced by this device is a series of "clicks" that form a distinctly different sound from the usual din from air conditioners, engines, and airflow.

These are some of the "tricks" used by the simulator technologists to create the sounds. It is still up to the researcher to establish what aircraft parameters control these sounds. With some components, this is simple. Turboprop and turbojet engine noises require the calculation of a parameter proportional to engine speed and thrust level.

Airflow noises are proportional to airspeed squared or dynamic pressure. Air conditioning noise level is proportional to blower speed. Thrust reverser noise is proportional to thrust. Runway rumble is proportional to ground speed and weight on the wheels. Gear actuation and runway rumble sounds are often controlled only by discrete signals indicating the event.

When setting up a sound simulation and depending on its importance to the problem to be solved, some subjective evaluations of the sound simulation will be required, particularly if the variables controlling the sound cannot be readily identified and computed. The dynamics of the sound generator cause time delays. These delays must be adjusted to zero and

the appropriate dynamics used for control. It is advisable not to use the inherent adjustable delays of the generator itself but rather make them zero and insert the required dynamics into the control variables sent to the generator. In all cases the researcher must provide a definition of sound control variables and be responsible for accepting the final result.

SECTION 4

VISUAL DISPLAY SYSTEM

4.1 GENERAL DESCRIPTION

The visual image of the outside world is presented to the pilot by a color television system whereby a camera looks at a model of a section of the earth's surface. The camera is driven relative to the model in the same way that the aircraft moves relative to the real world, thus creating a dynamic image of the outside world. A monitor placed before the pilot displays this scene through a collimating lens system that focuses the image at infinity. The central computer which solves the aircraft equations of motion performs additional calculations of where the pilot's eye point is relative to the earth and sends this information to the camera drive system.

4.1.1 TERRAIN MODELS

The terrain model associated with each Visual Flight Attachment (VFA) is composed of removeable panels that collectively form a three-dimensional color model of several different types of airports and surrounding terrain. The panels can be repositioned or specially tailored to meet the requirements of a particular simulation program. Currently there are three terrain models available for use in conjunction with the FSAA. These are the VFA-07 and two separate sections of the VFA-02.

The VFA-07 terrain model contains several different types of airports. A conventional airport is scaled at 600/1 with runway dimensions of 61 x 3048 m (200 x 8000 ft). There are threshold lights available on Runway 09 for night landings. In addition to the CTOL runway, there are STOL, RTOL, VTOL, and dirt runways. All of these runways are scaled at 600/1. There is also a 400/1 scale aircraft carrier that has pitch, roll, and heave

capabilities (the ship motion is controlled by the digital computer). The major features of the VFA-07 terrain model are shown in the photograph of Figure 4.1.1-1.

As mentioned above, the VFA-02 terrain model contains two different kinds of earth features. On one half of the board, the area around a STOL port is represented in color at a scale of 600/1. The runway dimensions of this model is shown in Figure 4.1.1-2. No lighting is available for night operation.

The other half of the VFA-02 board contains a color model of the hill country near the Hunter-Liggett Army Base, California. The scale of this model is 400/1 which makes it suitable for low-level operations of helicopters. Details of this model are shown in Figure 4.1.1-3.

4.1.2 CAMERA PROBE AND GANTRY ASSEMBLY

The television camera is carried over each model by a track, wheel, and tower assembly that imparts three orthogonal linear movements to the camera. The terrain models are all mounted vertically. The longest track is on the floor beside the model. This axis simulates east/west motion and carries a shorter vertical tower that provides north/south movement. This tower carries the ways for the shortest horizontal axis which moves the camera toward or away from the model, simulating altitude changes.

The optical probe assembly is arranged so that the "entrance pupil" (equivalent to the pilot's eye point) is on the intersection of all three gimbal axes. In this way, control of the translation of the pilot's eye point may be kept independent of the effective pointing of the camera. The probe assembly is designed to carry the pilot's eye point very close to the model for simulating low altitude. Portions of the probe and gantry may be seen in Figures 4.1.1-1, 4.1.1-2, and 4.1.1-3.
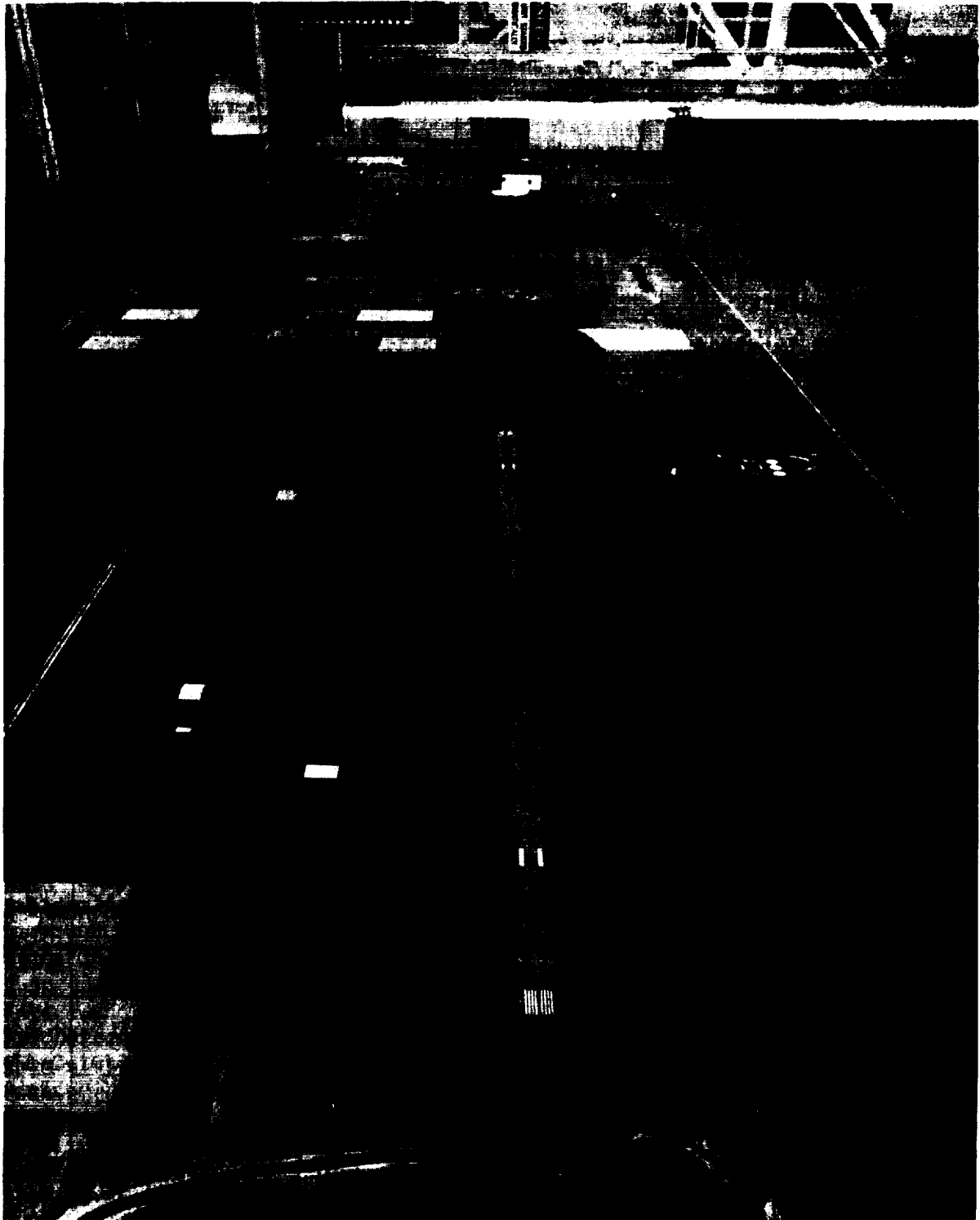
Figure 4.1.1-1: VFA-07 Terrain Model Details
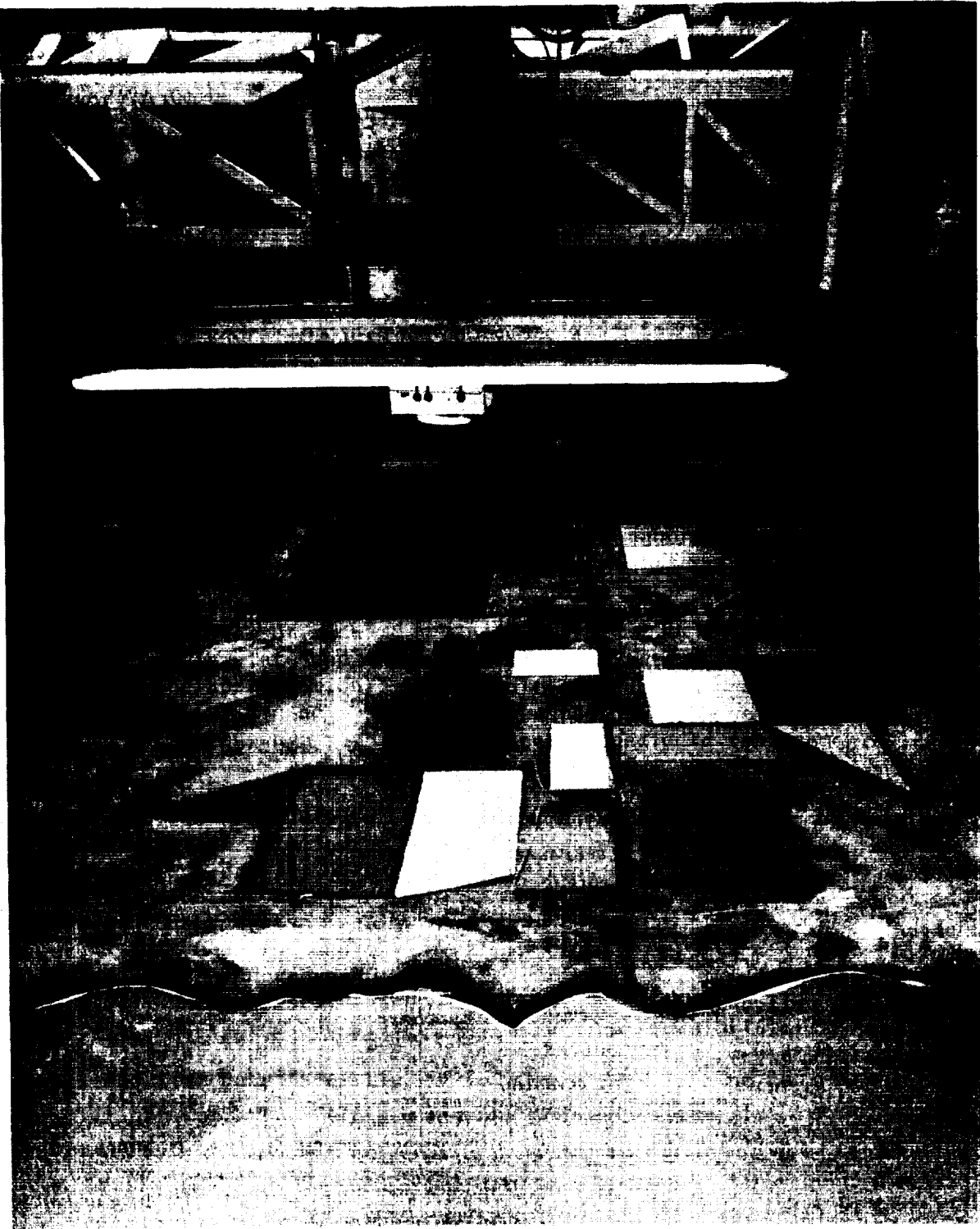
Figure 4.1.1-2: The Portion of the VFA-02 Terrain Model
                 Representing a STOL Port
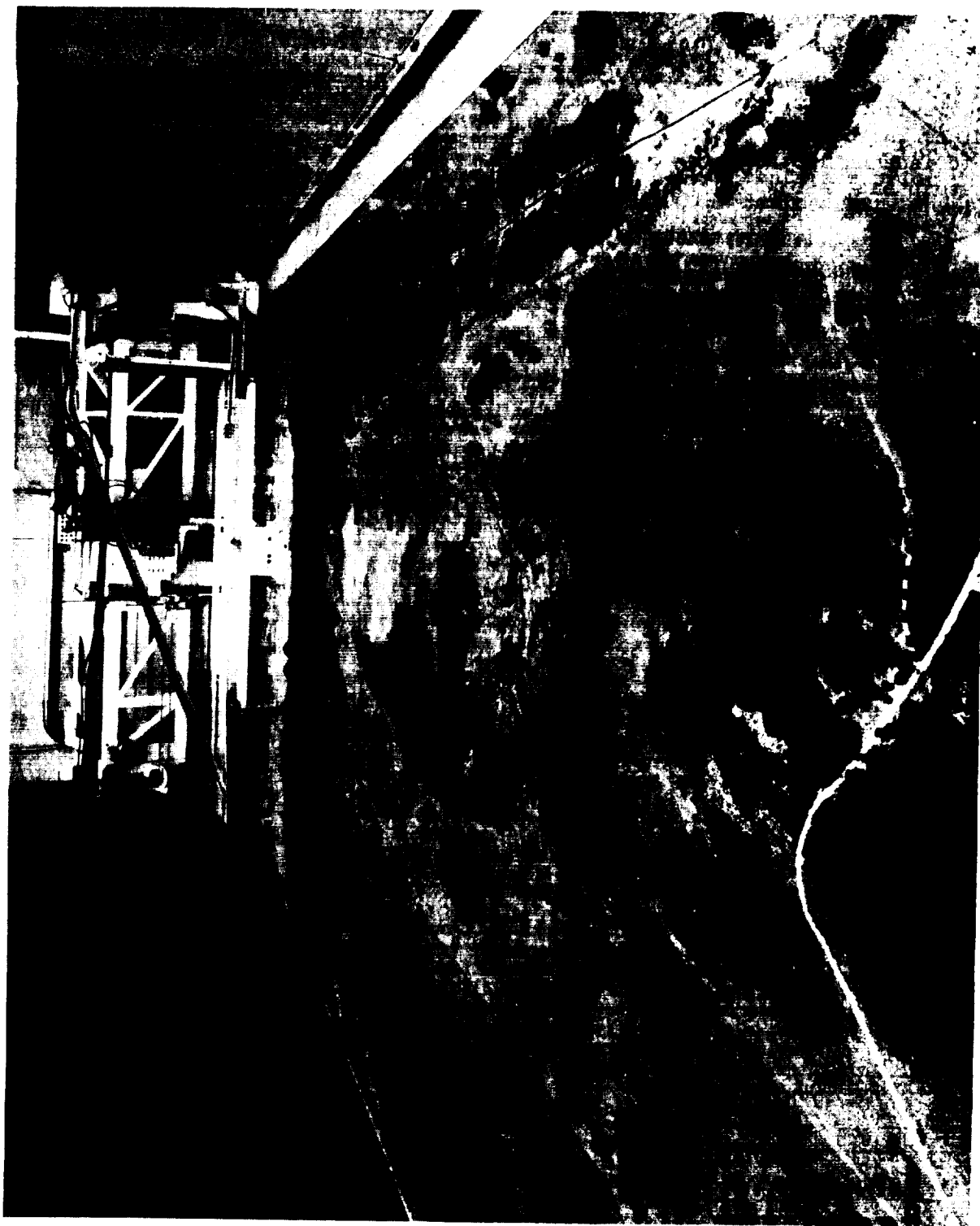
Figure 4.1.1-3: The Portion of the VFA-02 Terrain Model
Representing the California Hill Country Near the Hunter-Liggett Army Air Base

4.1.3 OPERATOR CONTROL STATION AND INTERFACE EQUIPMENT

Adjacent to the terrain models and gantries, an operator's station contains both television and servo interfacing equipment that is used to maintain and control the monitor images and the servo motors. The usual complement of television equipment is used to monitor and adjust each image. Unique equipment is incorporated into these units from which electronic fog is generated. The focus drive is also controlled here. An analog computer is used to provide scaling, filtering, and additional function generation for the focus drive. Test inputs may be applied at this computer. Servo monitoring and control are performed here and auxiliary test equipment such as oscilloscopes and recorders are available. The operator generally requires one hour to activate the system. Thereafter, it is automatically controlled by the central computer.

4.1.4 COCKPIT MONITORS

A 63.5 cm (25 inch) color monitor is placed before each seat in an enclosure sealed from outside light. Their faces are located 76.2 cm (30 inches) from the inside window face. Adjustments to these monitors are made from the platform atop the cockpit.

4.1.5 COLLIMATING LENS SYSTEMS

The inside window faces of the cockpit enclosure containing the monitors are actually the flat surfaces of one of two large lenses that effectively form a virtual image of the television picture at infinity. This lens system consists of two plano-convex plastic lenses mounted close together with their spherical surfaces facing each other. The focal length of the combination is 61.0 cm (24 inches). The lenses are mounted in the enclosure openings so that the television monitor face is in the far focal plane. The pilot's eye point (viewing point) is generally close to the near focal plane so that light radiating from any point on the television monitor face is refracted nearly parallel upon passing through the lens, thus forming a virtual image at optical infinity of the monitor face.

4.2 SERVOSYSTEM CHARACTERISTICS

4.2.1 MAXIMUM AND MINIMUM PERFORMANCE

All the servomechanisms of the visual display are the electrical type. They are basically electric motors whose steady state speed is proportional to the error input. The error is formed by the difference between the command position and the actual servo position as sensed by position potentiometers. The position loop is closed through the analog computer and the position commands are provided by the central digital computer.

The yaw and roll axes of the probe are capable of continuous rotation while the pitch axis travel is limited. Due to their inherent design, they all experience limitations in the maximum accelerations, velocities, and displacements (except yaw and roll) that can be produced. These are listed in Table 4.2.1-1. Commanded values greater than the ones listed in Table 4.2.1-1 will result in the servos holding to those values. The minimum performance of the servos is primarily affected by feedback potentiometer resolution, gear backlash, and friction. Due to these factors, the minimum performance, or threshold, is defined in two ways. The first threshold encountered is the one defined as when the controlled axis just shows movement. The second (higher) threshold is defined as when the controlled axis movement shows high correlation with the computer command. The latter threshold is primarily a function of the feedback potentiometer resolution.

The values of these thresholds are also listed in Table 4.2.1-1. Table 4.2.1-2 lists the translational performance that would be present in the simulated worlds at the two model scales of 400/1 and 600/1. These were obtained by simply multiplying the translational performance values by 400 and 600, respectively.

4.2.2 FREQUENCY RESPONSE

The frequency responses, as measured by the SAFE program described in Section 5.3.2, are presented in Figure 4.2.2-1 for all the servomechanisms

TABLE 4.2.1-1

MAXIMUM AND MINIMUM PERFORMANCE OF THE VFA-07 AND VFA-02 VISUAL DISPLAY SERVOSYSTEMS

AXIS / VARIABLE	ROLL	PITCH	YAW	X (EAST-WEST)	Y (NORTH-SOUTH)	Z (HEIGHT)
MAXIMUM DISPLACEMENT	Continuous	$\pm$ 25 deg	Continuous	$\pm$ 11 m	$\pm$ 2.3 m	$\pm$ 0.61 m
MAXIMUM VELOCITY	$\pm$ 315 deg/sec	$\pm$ 143 deg/sec	$\pm$ 218 deg/sec	$\pm$ 0.21 m/sec	$\pm$ 0.27 m/sec	$\pm$ 0.43 m/sec
MAXIMUM ACCELERATION	$\pm$ 90 deg/sec^2	$\pm$ 1260 deg/sec^2	$\pm$ 1719 deg/sec^2	$\pm$ 0.30 m/sec^2	$\pm$ 0.30 m/sec^2	$\pm$ 0.55 m/sec^2
FIRST MOVEMENT THRESHOLD	$\pm$ 0.17 deg	$\pm$ 0.03 deg	$\pm$ 0.17 deg	$\pm$ 2.13 mm	$\pm$ 0.46 mm	$\pm$ 1.22 mm
HIGH CORRELATION THRESHOLD	$\pm$ 0.24 deg	$\pm$ 0.18 deg	$\pm$ 0.34 deg	$\pm$ 6.4 mm	$\pm$ 2.29 mm	$\pm$ 2.29 mm

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TABLE 4.2.1-1 (Concluded)

VFA-02

AXIS / VARIABLE	ROLL	PITCH	YAW	X (EAST-WEST)	Y (NORTH-SOUTH)	Z (HEIGHT)
MAXIMUM DISPLACEMENT	Continuous	$\pm$ 25 deg	Continuous	$\pm$ 11 m	$\pm$ 1.2 m	$\pm$ 0.19 m
MAXIMUM VELOCITY	$\pm$ 315 deg/sec	$\pm$ 143 deg/sec	$\pm$ 218 deg/sec	$\pm$ 0.15 m/sec	$\pm$ 0.15 m/sec	$\pm$ 0.091 m/sec
MAXIMUM ACCELERATION	$\pm$ 90 deg/sec^2	$\pm$ 1260 deg/sec^2	$\pm$ 1719 deg/sec^2	$\pm$ 0.24 m/sec^2	$\pm$ 0.24 m/sec^2	$\pm$ 0.091 m/sec^2
FIRST MOVEMENT THRESHOLD	$\pm$ 0.17 deg	$\pm$ 0.03 deg	$\pm$ 0.17 deg	- - -	$\pm$ 0.52 mm	$\pm$ 0.52 mm
HIGH CORRELATION THRESHOLD	$\pm$ 0.24 deg	$\pm$ 0.18 deg	$\pm$ 0.34 deg	$\pm$ 6.4 mm	$\pm$ 2.3 mm	$\pm$ 2.3 mm

TABLE 4.2.1-1

MAXIMUM AND MINIMUM PERFORMANCE OF THE VFA-07 and VFA-02 VISUAL DISPLAY SERVOSYSTEMS

VFA-07

AXIS / VARIABLE	ROLL	PITCH	YAW	X (EAST-WEST)	Y (NORTH-SOUTH)	Z (HEIGHT)
MAXIMUM DISPLACEMENT	Continuous	$\pm$ 25 deg	Continuous	$\pm$ 36 ft	$\pm$ 7.5 ft	$\pm$ 2 ft
MAXIMUM VELOCITY	$\pm$ 315 deg/sec	$\pm$ 143 deg/sec	$\pm$ 218 deg/sec	$\pm$ 0.68 ft/sec	$\pm$ 0.9 ft/sec	$\pm$ 1.4 ft/sec
MAXIMUM ACCELERATION	$\pm$ 90 deg/sec^2	$\pm$ 1260 deg/sec^2	$\pm$ 1719 deg/sec^2	$\pm$ 1 ft/sec^2	$\pm$ 1 ft/sec^2	$\pm$ 1.8 ft/sec^2
FIRST MOVEMENT THRESHOLD	$\pm$ 0.17 deg	$\pm$ 0.03 deg	$\pm$ 0.17 deg	$\pm$ 0.007 ft	$\pm$ 0.0015 ft	$\pm$ 0.004 ft
HIGH CORRELATION THRESHOLD	$\pm$ 0.24 deg	$\pm$ 0.18 deg	$\pm$ 0.34 deg	$\pm$ 0.021 ft	$\pm$ 0.0075 ft	$\pm$ 0.0075 ft

TABLE 4.2.1-1 (Concluded)

VFA-02

VARIABLE \ AXIS	ROLL	PITCH	YAW	X (EAST-WEST)	Y (NORTH-SOUTH)	Z (HEIGHT)
MAXIMUM DISPLACEMENT	Continuous	$\pm$ 25 deg	Continuous	$\pm$ 36 ft	$\pm$ 4 ft	$\pm$ 0.625 ft
MAXIMUM VELOCITY	$\pm$ 315 deg/sec	$\pm$ 143 deg/sec	$\pm$ 218 deg/sec	$\pm$ 0.5 ft/sec	$\pm$ 0.5 ft/sec	$\pm$ 0.3 ft/sec
MAXIMUM ACCELERATION	$\pm$ 90 deg/sec^2	$\pm$ 1260 deg/sec^2	$\pm$ 1719 deg/sec^2	$\pm$ 0.8 ft/sec^2	$\pm$ 0.8 ft/sec^2	$\pm$ 0.3 ft/sec^2
FIRST MOVEMENT THRESHOLD	$\pm$ 0.17 deg	$\pm$ 0.03 deg	$\pm$ 0.17 deg	- - -	$\pm$ 0.0017 ft	$\pm$ 0.0017 ft
HIGH CORRELATION THRESHOLD	$\pm$ 0.24 deg	$\pm$ 0.18 deg	$\pm$ 0.34 deg	$\pm$ 0.021 ft	$\pm$ 0.0075 ft	$\pm$ 0.0075 ft

TABLE 4.2.1-2

TRANSLATIONAL MAXIMUM AND MINIMUM PERFORMANCE

AT THE TWO MODEL SCALES 400/1 and 600/1

VFA-02   400/1

AXIS / VARIABLE	X (EAST-WEST)	Y (NORTH-SOUTH)	Z (HEIGHT)
"FLY-IN" BOX DIMENSIONS	8.77 km	0.98 km	152.4 m
MAXIMUM VELOCITY	± 60.7 m/s	± 60.7 m/s	± 36.6 m/sec
MAXIMUM ACCELERATION	± 9.9 g's	± 9.9 g's	± 3.7 g's
FIRST MOVEMENT THRESHOLD	- - -	0.21 m	0.21 m
HIGH CORRELATION THRESHOLD	2.6 m	0.91 m	0.91 m

VFA-02   600/1

AXIS / VARIABLE	X (EAST-WEST)	Y (NORTH-SOUTH)	Z (HEIGHT)
"FLY-IN" BOX DIMENSIONS	13.2 km	1.46 km	228.6 m
MAXIMUM VELOCITY	± 91.6 m/s	± 91.6 m/s	± 54.9 m/sec
MAXIMUM ACCELERATION	± 14.9 g's	± 14.9 g's	± 5.6 g's
FIRST MOVEMENT THRESHOLD	- - -	0.30 m	0.30 m
HIGH CORRELATION THRESHOLD	3.8 m	1.4 m	1.4 m

TABLE 4.2.1-2 (Concluded)

VFA-07   600/1

AXIS VARIABLE	X (EAST-WEST)	Y (NORTH-SOUTH)	Z (HEIGHT)
"FLY-IN" BOX DIMENSIONS	13.2 km	2.7 km	739.5 m
MAXIMUM VELOCITY	$\pm$ 124.5 m/s	$\pm$ 164.6 m/s	$\pm$ 256.0 m/s
MAXIMUM ACCELERATION	$\pm$ 18.6 g's	$\pm$ 18.6 g's	$\pm$ 33.5 g's
FIRST MOVEMENT THRESHOLD	1.3 m	0.27 m	0.73 m
HIGH CORRELATION THRESHOLD	3.8 m	1.4 m	1.4 m

TABLE 4.2.1-2

TRANSLATIONAL MAXIMUM AND MINIMUM PERFORMANCE

AT THE TWO MODEL SCALES 400/1 and 600/1

VFA-02 400/1

VARIABLE \ AXIS	X (EAST-WEST)	Y (NORTH-SOUTH)	Z (HEIGHT)
"FLY-IN" BOX DIMENSIONS	5.45 mi	0.61 mi	500 ft
MAXIMUM VELOCITY	± 118 kt	± 118 kt	± 7200 ft/min
MAXIMUM ACCELERATION	± 9.9 g's	± 9.9 g's	± 3.7 g's
FIRST MOVEMENT THRESHOLD	- - -	0.68 ft	0.68 ft
HIGH CORRELATION THRESHOLD	8.4 ft	3.0 ft	3.0 ft

VFA-02 600/1

VARIABLE \ AXIS	X (EAST-WEST)	Y (NORTH-SOUTH)	Z (HEIGHT)
"FLY-IN" BOX DIMENSIONS	8.18 mi	0.91 mi	750 ft
MAXIMUM VELOCITY	± 178 kt	± 178 kt	± 10800 ft/min
MAXIMUM ACCELERATION	± 14.9 g's	± 14.9 g's	± 5.6 g's
FIRST MOVEMENT THRESHOLD	- - -	1.0 ft	1.0 ft
HIGH CORRELATION THRESHOLD	12.6 ft	4.5 ft	4.5 ft

TABLE 4.2.1-2 (Concluded)

VFA-07   600/1

AXIS VARIABLE	X (EAST-WEST)	Y (NORTH-SOUTH)	Z (HEIGHT)
"FLY-IN" BOX DIMENSIONS	8.2 mi	1.7 mi	2400 ft
MAXIMUM VELOCITY	± 242 kt	± 320 kt	± 50400 ft/min
MAXIMUM ACCELERATION	± 18.6 g's	± 18.6 g's	± 33.5 g's
FIRST MOVEMENT THRESHOLD	4.2 ft	0.9 ft	2.4 ft
HIGH CORRELATION THRESHOLD	12.6 ft	4.5 ft	4.5 ft
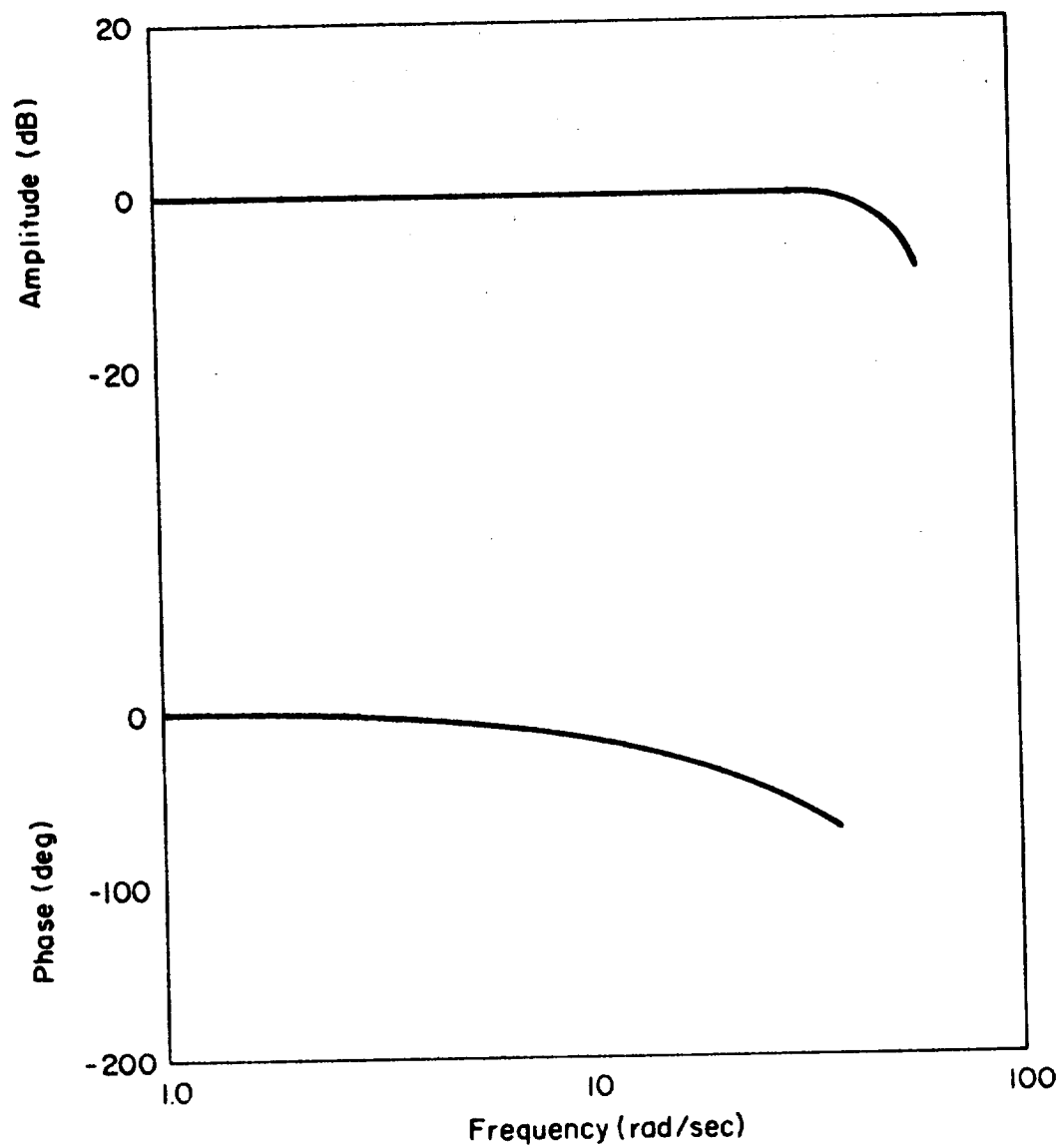
Figure 4.2.2-1: SAFE Frequency Response Functions for
the VFA-07 Visual System

a. VFA-07 ROLL
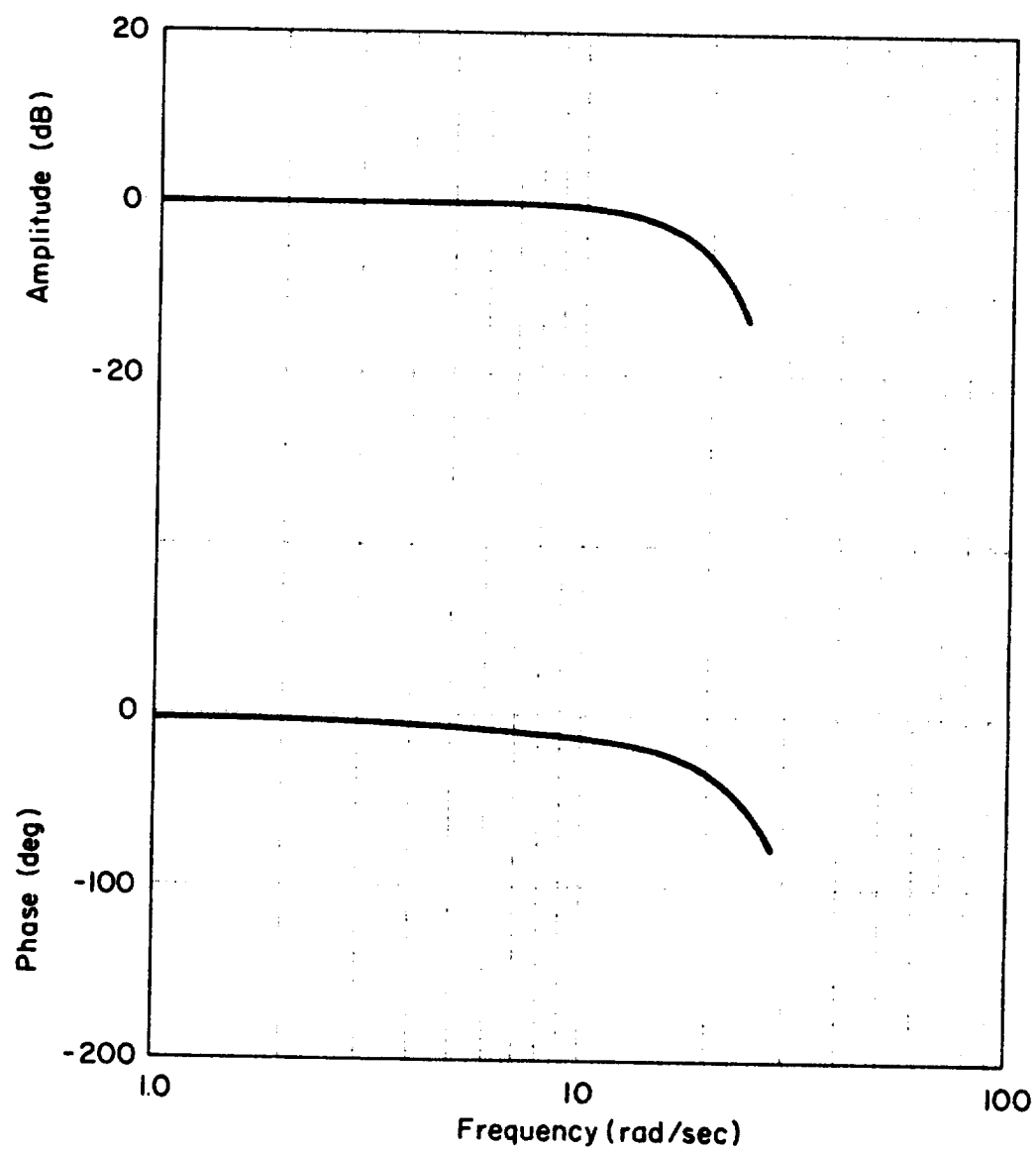
Figure 4.2.2-1 (Continued)

b. VFA-07 PITCH
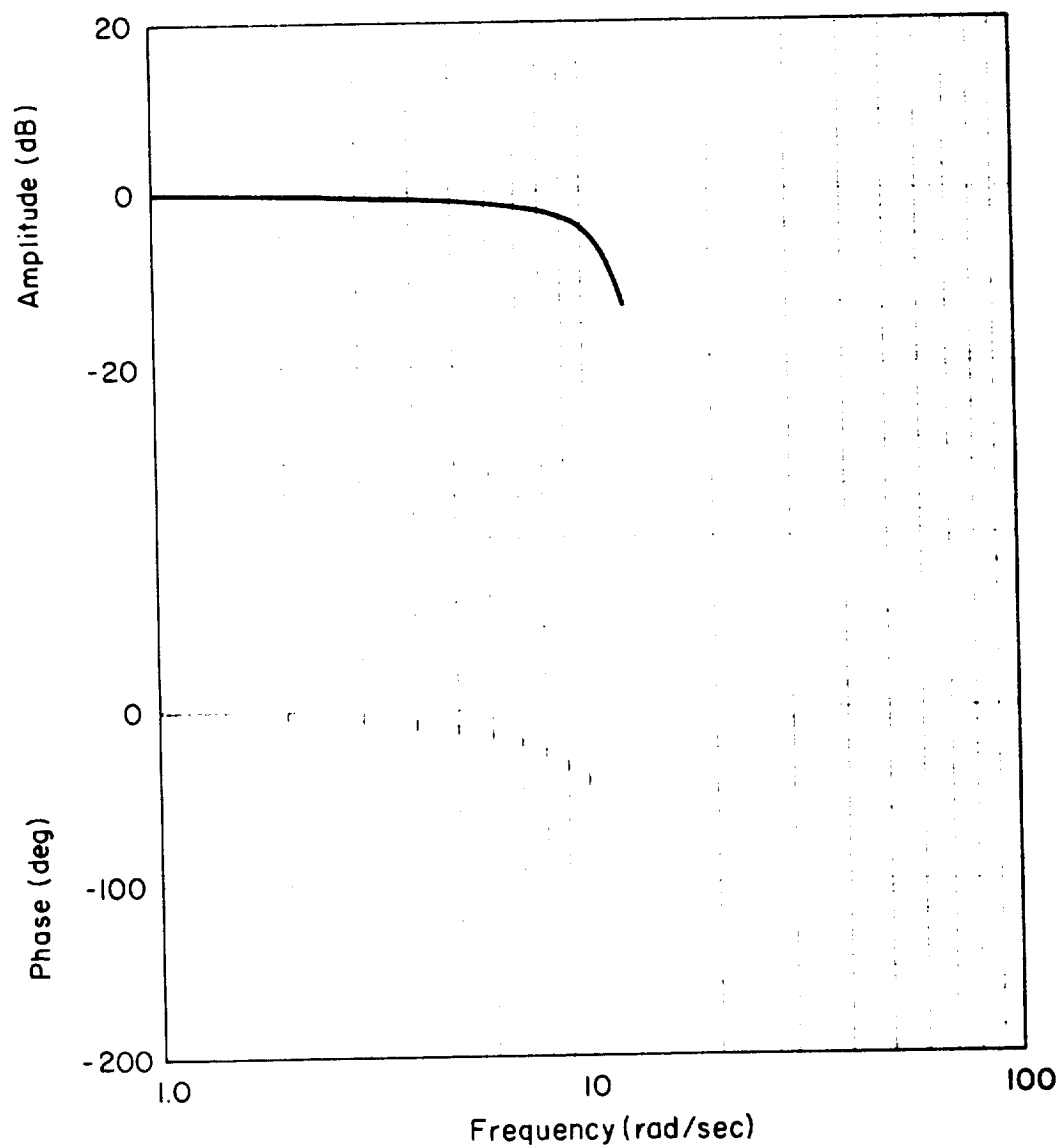
Figure 4.2.2-1 (Continued)

c. VFA-07 HEADING

IV-18
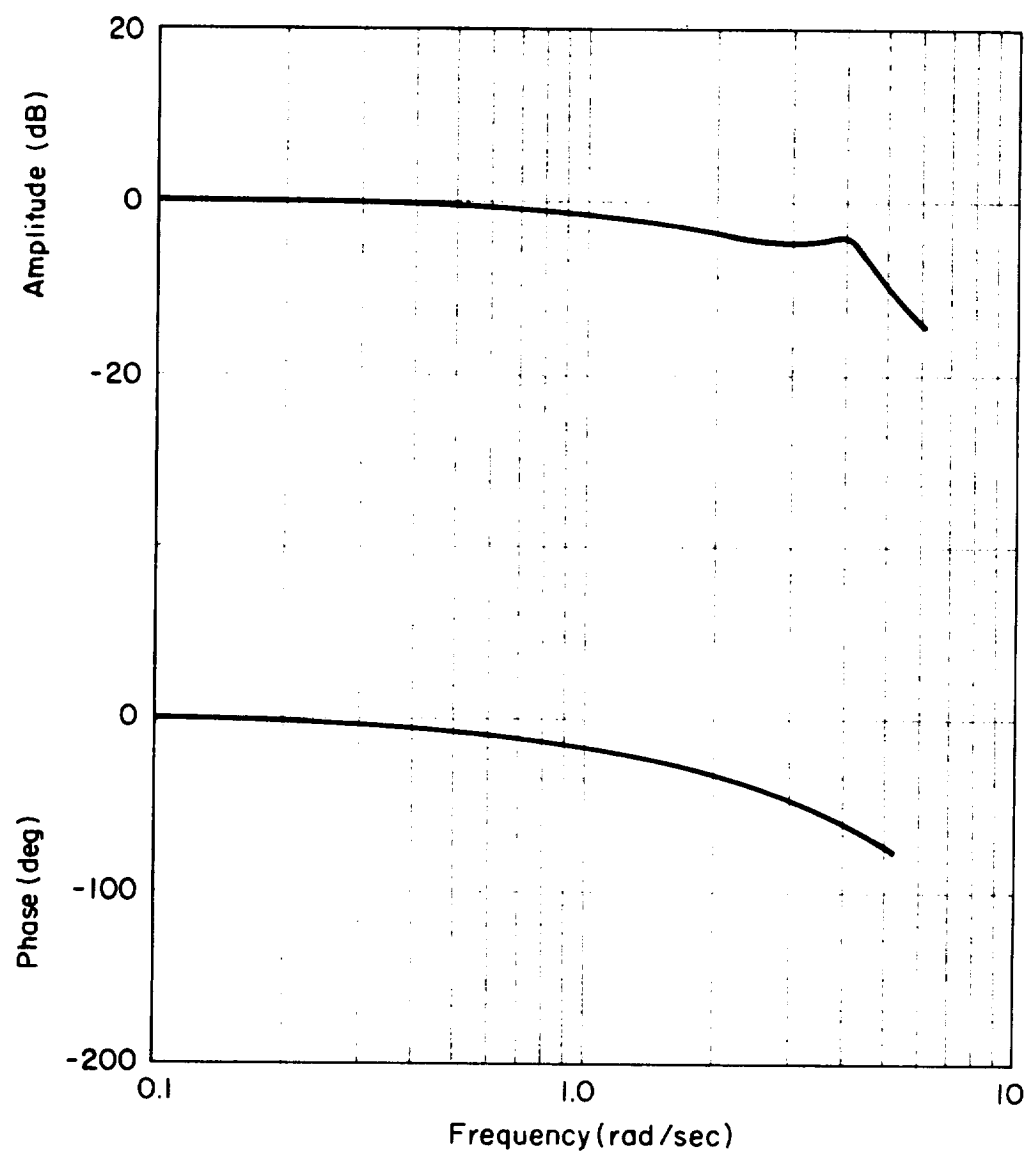
Figure 4.2.2-1 (Continued)

d. VFA-07 EAST-WEST

IV-19
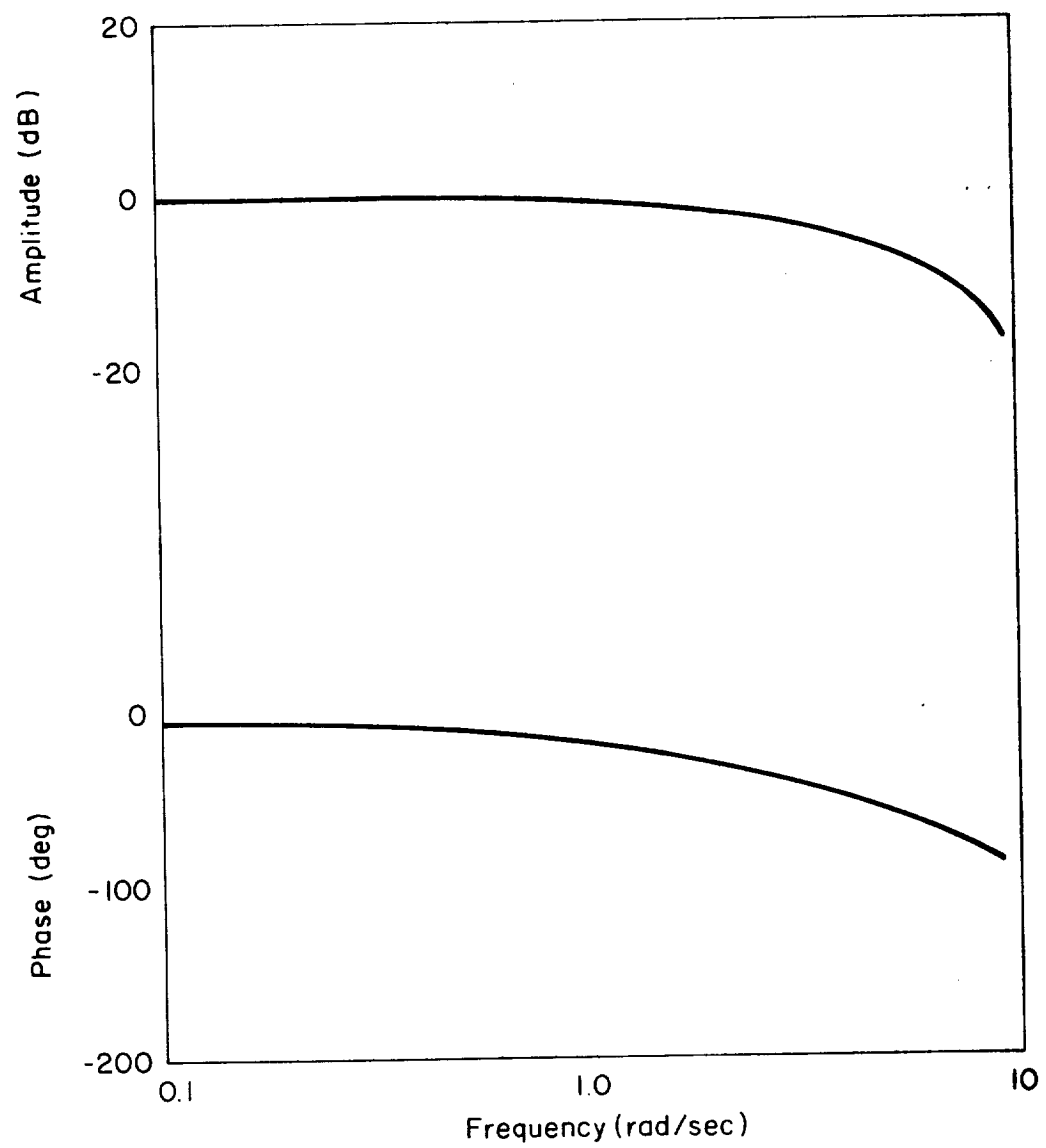
Figure 4.2.2-1 (Continued)

e. VFA-07 NORTH-SOUTH

IV-20
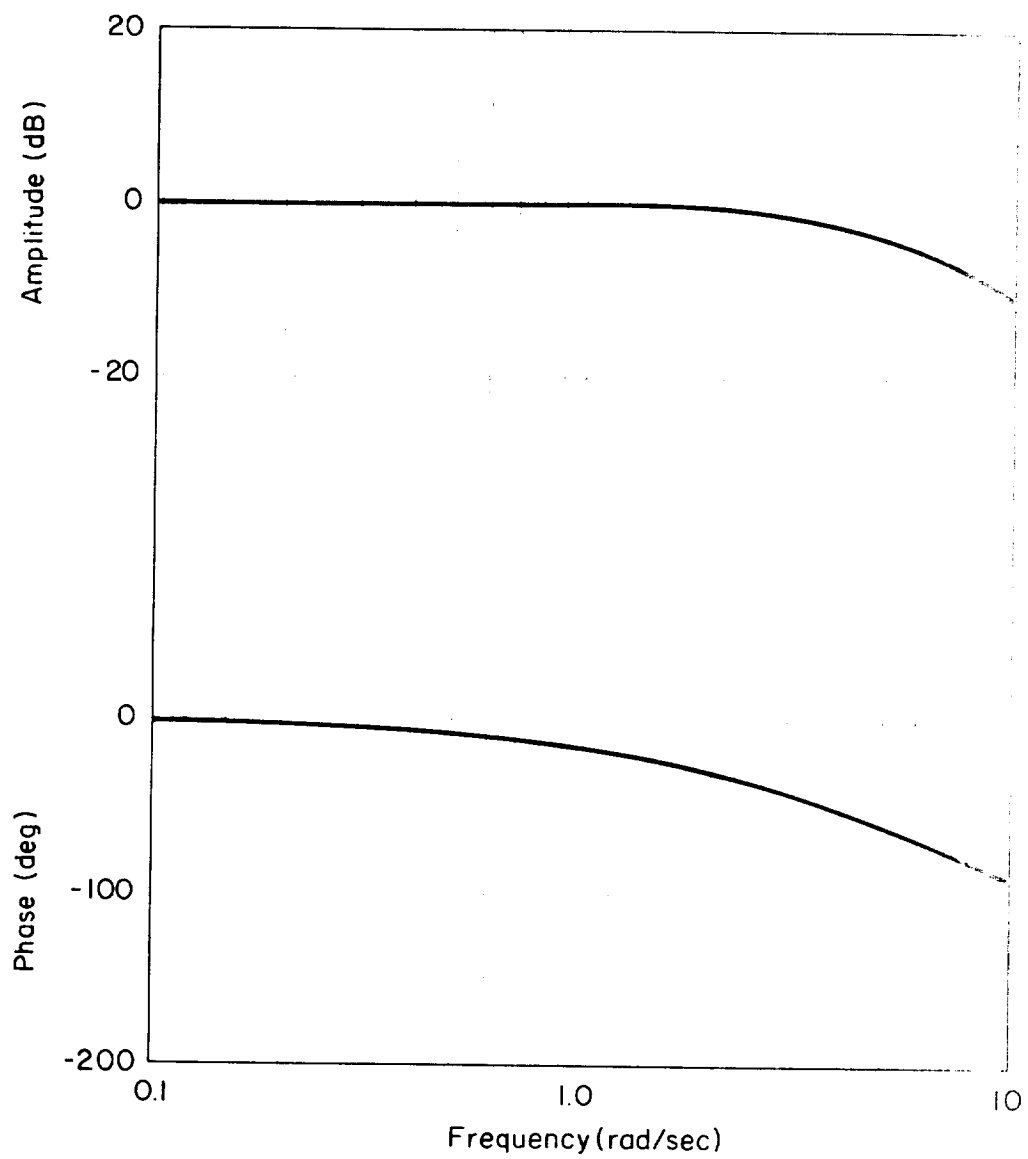
Figure 4.2.2-1 (Concluded)

f. VFA-07 ALTITUDE

except the focus drive. Note that the performance of the servos is not uniform and that the performance of the smaller mass rotational servos is better than that for the translational ones. The data shown are for input commands greater than the threshold. The peak values of the driving sinusoids for these data were $\pm$ 0.1 radian and $\pm$ 3.05 cm ($\pm$ 0.1 ft).

4.2.3 POSITION ERROR

The servos are driven by position commands and position feedbacks. As such, they will have a steady state position error when responding to ramp position commands or constant velocity. Since the translational axes will have driving functions that are typically ramps of position or constant velocity, it is important to know the values of these errors. Measurements have shown the error to be 0.33 times the velocity command. What this says is that the displayed scene viewing point (pilot's eye) will lag behind the commanded position a constant distance when velocity commands are constant. This lag, expressed in time, is about 0.33 seconds. Some typical error values for two typical model scales are tabulated in Table 4.2.3-1. These errors may be reduced by adding lead to the drive command (adding a portion of velocity command to the position command). Provisions for this are incorporated into the drive software. The leads are designed to offset these lags as well as lags purposely patched into the analog drive circuits that are sometimes required to smooth the stairstep digital drive commands.

4.2.4 RESET TIMES

When the terminal position of the simulated aircraft is widely different from the IC position it takes an appreciable time to return the camera to the IC position. These reset times may be the most significant part of the restart cycle and therefore should be considered in a run plan using the outside visual scene. The maximum reset time for the X axis is easily found by dividing the double amplitude of the X axis by the peak X velocity capability. This is 2 x 36 / 0.68 = 106 seconds for the VFA-07

TABLE 4.2.3-1

TYPICAL POSITION ERRORS DUE TO VELOCITY COMMAND

SCALE	1	400/1	600/1
VELOCITY	1.0 m/sec	31.0 m/s	46.4 m/s
POSITION ERROR	0.33 m	10.1 m	15.2 m

TABLE 4.2.3-1

TYPICAL POSITION ERRORS DUE TO VELOCITY COMMAND

SCALE	1	400/1	600/1
VELOCITY	1.0 ft/sec	60 kt	90 kt
POSITION ERROR	0.33 ft	33.2 ft	49.8 ft

model and 2 x 36 / 0.5 = 144 seconds for the VFA-02 model. When the initial condition does not require an outside scene (such as IFR operations), the reset times are not important as the simulation can be restarted while the camera is still returning to the IC position. The only constraint is that the camera catch up before the pilot goes visual.

4.3 DRIVE LOGIC

4.3.1 DIGITAL DRIVE LOGIC

Within the BASIC software is a subroutine, BVISUAL, which computes the linear and angular commands to the VFA camera servos. The subroutine also determines if the visual scene is to be fogged or clear. Program inputs, outputs, and special features are shown in Figures 4.3.1-1 and 4.3.1-2 and described below.

A. Primary Program Inputs and Outputs

INPUTS

1. The position of the pilot's eye point with respect to a runway axis system (XPR,YPR,HPR).

2. The orientation of the pilot relative to the runway (i.e., the aircraft Euler angles). The actual program input is the Earth-to-Body axis transformation matrix elements.

3. The fog ceiling (HFOGB). That is, the visual scene is "fogged" when the aircraft altitude is greater than HFOGB.

OUTPUTS

1. The linear servo command signals (XREDCO,YREDCO,HREDCO).

2. The angular servo command signals (PSIRED and PSIBLK, THTRED and PHIRED). There are two signals required for
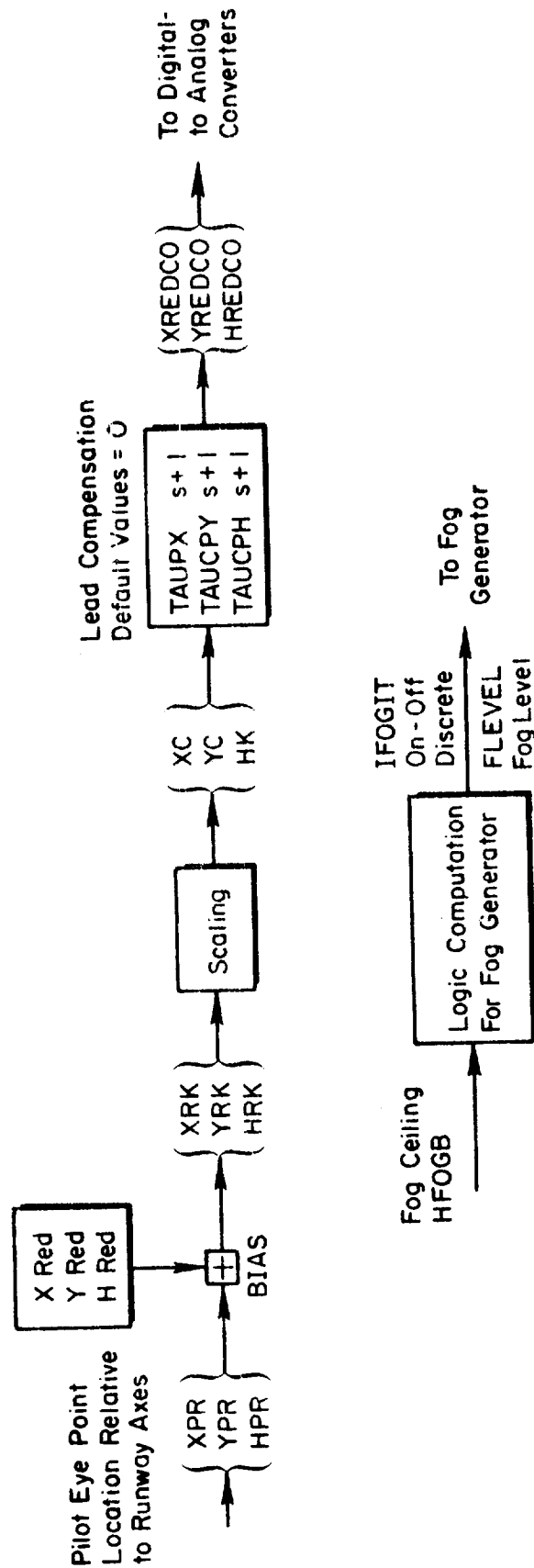
Figure 4.3.1-1: Visual System Digital Drive Logic (BVISUAL) For the Probe Translational Axes
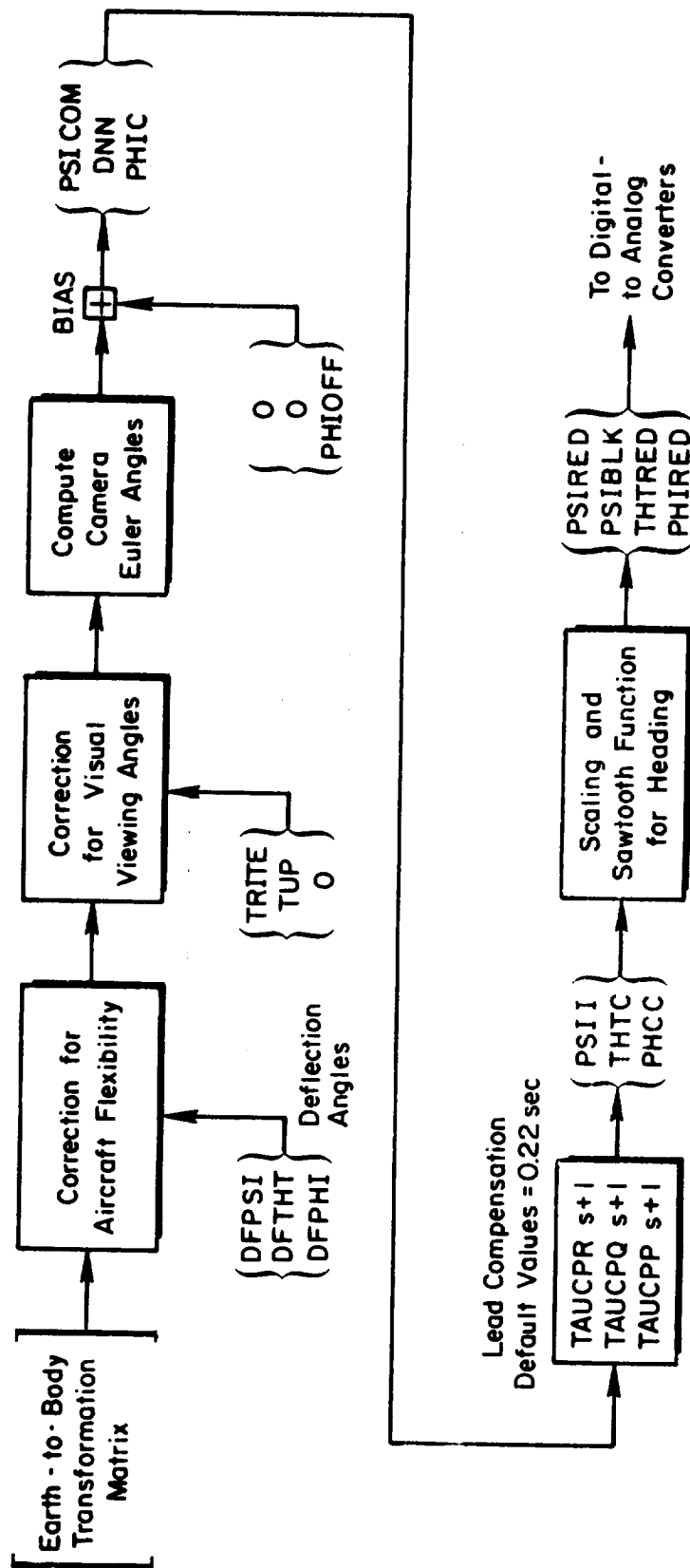
Figure 4.3.1-2: Visual System Digital Drive Logic (BVISUAL)
For the Probe Rotational Axes

heading because of the continuous nature of the
heading servo.

3. The fog ON/OFF discrete (IFOGIT), and the fog level
(FLEVEL). The fog discrete is used to blank out the
visual scene when the camera errors are large (e.g.,
during the reset to the IC position). The fog level,
FLEVEL, is HFOGB converted from feet to volts.

B. Scaling

The pilot position and orientation are converted to voltage
commands for the camera servos.

C. Biasing

Linear and angular biasing is achieved by setting the
following Fortran variables:

    Altitude   = HRED
    East/west position   = XRED
    North/south position   = YRED
    Roll   = PHIOFF

These biases are used to align the camera and runway axes.

D. Lead Compensation

This option permits first-order lead compensation to be
added to any of the camera servo position commands, the
purpose of this being to cancel some of the inherent or
intentional lag (digital smoothing filter) in the camera
dynamics. The default values of the lead time constants
are equal to zero for the translational commands and equal
to 0.22 seconds for the rotational commands.

E. Fog

The visual scene is fogged when the camera servos are not following the commands. This is done for two reasons.

1. If the camera hits a physical stop the pilot will not be shown an erroneous scene.

2. If the computer goes to Operate while the camera is returning to IC, the pilot will not be shown a scene moving backwards.

F. Pop-Up Logic

The purpose of this logic is to protect the model scenery and camera probe from collision damage. This is accomplished as follows:

If the camera servos are commanded to move while in the IC mode (e.g., change XIC,YIC,HIC) and the aircraft altitude is less than 15.2 m (50 feet), then the camera is raised up prior to moving horizontally to the new IC position. The camera probe is thus prevented from striking the model scenery while moving to the new IC position. The visual scene is always fogged during this operation.

G. Visual Viewing Angle

If an aircraft is configured such that the pilot's viewing angle is not aligned with the fuselage reference line (e.g., the Concorde) then the aircraft Euler angles cannot be used to drive the camera servos. The scheme used to accomplish this employs two angles defined in the pitch, yaw order of rotation (TUP and TRITE). Perturbation components of the direction cosine matrix calculated from these angles are

added to those normally computed from the Euler angles.
The resulting matrix is then used to extract the three
Euler angles for the camera servos.

H. Flexible Aircraft Option

If IFLEX = 1, perturbation angles are used to modify the
Earth-to-Body transformation matrix. This modification is
based on the small angle approximations for the effects of
the perturbations.

I. Auxiliary Runway Option

Two alternate runways can be specified for use. This option
is most commonly used for landing on an aircraft carrier.
The following Fortran variables must be set:

ISHIP   = Switch for specifying the runway to be used
        = 0 for nominal runway
        = 1 for ship 1
        = 2 for ship 2

XSHIP1, YSHIP1, HSHIP1 = origin of ship 1 runway threshold

XSHIP2, YSHIP2, HSHIP2 = origin of ship 2 runway threshold

J. Mosaic Scene Option

This option is used when a high altitude visual scene is
required. The user is responsible for specifying the
necessary changes to the Redifon scenery. The following
Fortran variables also must be set:

MOSAIC = 1 (default 0)

XM, YM = Location of mosaic scene center

HTP   = Minimum altitude that mosaic scene is to be
          used

SSCALE = Multiple of nominal visual scene, e.g., if
nominal scale is 600/1 and SSCALE is equal to
2, then MOSAIC scale is 1200/1.

4.3.2 ANALOG DRIVE LOGIC

An analog computer is interfaced between the central digital computer
and the visual system. It is used to condition the drive commands, perform
scaling, biasing, monitoring, and switching for local control. Besides
these functions, the computer contains first-order lags designed to smooth
the digital step commands, and calculates the focus drive command. An
eight-channel brush recorder is available for monitoring of the many
voltages generated by this computer. The researcher can specify the focus
drive command function or he may elect to use the nominal drive program
available. This program computes a focus distance as a function of altitude
and pitch angle. The intent is to bring the image into better focus at
low altitudes.

4.4 OPTICAL PROPERTIES

4.4.1 FIELD OF VIEW, ENTRANCE AND EXIT PUPILS

The field coverage of a visual system is one of its most important
properties. All visual systems have a finite field coverage and light
is vignetted or blocked by the physical stops or edges of the optical
elements. When one looks at objects through binoculars, it is obvious that
images are formed within a circular field that subtends an angular diameter
of about 50 degrees. Some wide-angle binoculars can achieve 60 to 70 degrees.
This field coverage is usually available when the viewer's eye is on the
optical axis. When the viewer's eye is off the optical axis, the peripheral
light rays are used. These will eventually be blocked by the edges or
stops of the lens elements as the viewer moves his eye more off-axis.

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The VFA-07 probe has an entrance pupil 0.6 mm in diameter. The objective lens is designed such that its entrance pupil is located in its front focal plane. The objective lens is located so that its entrance pupil is placed on the gimbal center of the probe rotational axes. All incoming light passing through the system must pass through this aperture. This creates the effective viewing point of the system and represents the pilot's eye point relative to the model. The entrance pupil is made physically small so as to simulate a small viewing area and so the probe may be made small enough so it can move close to the terrain model, simulating low altitude. The closest approach to the model possible is 3.2 mm (1/8 inch) so in terms of the two model scales of 400/1 and 600/1, this represents a minimum height of 1.3 and 1.9 m (4.2 and 6.3 feet), respectively. The probe optics are designed for an angular field diameter of approximately 60 degrees. The 3/4 aspect ratio (height-to-width ratio) of standard television systems results in a 36 degree vertical by 48 degree horizontal format (diagonal $\cong$ 60 degrees). It is this format that is imaged on the camera tube scan face and cannot be altered.

If the monitor alone is placed before the pilot to display the scene imaged by the camera, angular correctness must be maintained and a 63.5 cm (25 inch) diagonal tube would have to be placed 55.0 cm (21.6 inches) from the pilot's eye point. To produce images that appear "far away" (infinity), a plano-convex lens pair is placed approximately 61.0 to 76.2 cm (24 to 30 inches) from the pilot's eye. The effective focal length of these lenses is 61.0 cm (24 inches) and the monitor is actually placed in the focal plane behind the lenses. The lenses act as a magnifier that produces a virtual image of the monitor face at optical infinity. The lens system operated this way produces an angular magnification of two, therefore the monitor appears 36 degrees by 48 degrees in size.

When the picture is viewed sufficiently off axis, the edges of the monitor will appear. This occurs when the pilot's eye point (bridge of the nose) is placed about 7.6 cm (3 inches) off axis vertically and 10.2 cm (4 inches) horizontally. The allowable head motion is therefore a rectangle centered on the optical axis of the collimating lens system of dimensions 15.2 cm (6 inches) vertically and 20.3 cm (8 inches) horizontally. This is

a consequence of the monitor and lens diameters and cannot be altered.
Moving the eyes off-axis or toward or away from the picture results in no
observable perspective change.

4.4.2 STATIC AND DYNAMIC RESOLUTION

Resolution is that quality of any visual system to show fine detail.
The methods of describing this quality vary with the kinds of visual systems
discussed. Astronomers use the term "resolving power" to describe the
ability of telescopes to show the individual components of close double
stars. Optical engineers use "Modulation Transfer Function" to describe
resolution. Photo-optical and television technologists use the concepts
of "lines" and "line-pairs".

All these and other resolution criteria have one thing in common;
they employ a standard pattern of light that is easily recognized by either
the human eye or a photometric device. Inherent in the concept of resolu-
tion is yet another called "contrast ratio". When one speaks of "fine
detail", the idea of different light levels or luminance must be brought
forth. The only reason an object is seen at all is because its radiating
light levels are different from that of its surroundings. Therefore, fine
detail in a scene can be more easily seen if the detail contrasts with its
surroundings, i.e., shows a distinctly different pattern of light from its
surroundings. The concept of resolution is therefore intimately bound with
the concept of light level difference, i.e., luminance difference or
contrast.

Although many criteria are available, three are described here that are
commonly employed in measurement of the resolution of television visual
systems. For a more complete treatment of the subject the reader is
referred to Reference 4-1.

1. Resolving Power

An optical system of lenses such as a telescope forms images of
stars (point light sources) that are influenced primarily by diffraction

effects. For a circular aperture or lens opening, the light from a point source is spread into a series of bright concentric rings surrounding a much brighter central circle. The diameters of these circles and rings depends on the aperture diameter of the objective lens (the first lens the incoming light encounters) and the wavelength of the light. It is generally agreed that the light intensity drop midway between the central maxima of two equally bright overlapping diffraction patterns is relatively deep enough (about 30%) to appear clearly separated to the eye when the distance separating their centers is equal to the radius of the first interspace or minimum in the individual diffraction pattern. For light of mid-visible wavelengths (yellow-green), this leads to the relation:

$$r = \frac{1.97}{D} \text{ cm} \left(\frac{5}{D} \text{ inches} \right)$$

where

r is the resolving power in arc-seconds

D is the objective aperture in cm (inches)

The effective diameter of the probe objective is 0.6 mm which yield a value of r of 3.5 arc-minutes. For the human eye with a pupil diameter of 4 mm, the result is 0.5 arc-minutes. The resolving power of the eye is generally accepted as about one arc-minute, so the probe optics are worse than the eye in resolving two close point light sources of obvious high contrast.

2. Modulation Transfer Function

This is simply the system response to a sinusoidal luminance profile. A pattern of sinusoidally varying light intensity is used as an image. This resembles a series of light and dark bands. The system's response is measured by a photometer. The results generally depend on the quality of the hardware and vary with the mean luminance level, the contrast ratio (ratio of maximum to minimum luminance), and most importantly,

the frequency of the sinusoid expressed in terms of a linear or angular dimension. In the case of the latter, the resulting variable is cycles per degree of angular field and is termed the "spatial frequency". Most visual systems cannot respond to a sinusoidally varying luminance pattern when the spatial frequency becomes high, i.e., many bands form the object. A luminance difference of about 3% of the mean luminance is generally the limit of vision and spatial frequency at which this occurs can be taken as the system's visual limit. Even if it could resolve finer bands at lower luminance differences, they would not be visible.

The human visual system has its own modulation transfer function characteristic and measurements have shown humans to have maximum sensitivity to contrast (able to detect sinusoids of small contrast) at spatial frequencies of about 2 to 3 cycles/degree. Limiting spatial frequencies of high contrast for the television components of the VFA-07 visual system are generally about 5 cycles/degree, so the television limits are close to the optimum values of human vision.

3. Television Lines and Optical Line-Pairs

In the photo and electro-optical industry, the light patterns used for resolution measurements are called optical line-pairs. This refers to the number of bright and dark bands of a test object that can be imaged by the system. The luminance profile is rectangular and the system contrast is set up so the bright band is represented by the brightest white possible and the dark band by the darkest black possible. Television lines refer to the total number of lines that can just be imaged including all the white and black lines. An optical line-pair refers to one white line with half a black line on either side.

At contrast ratios of approximately 15/1, the VFA-07 cockpit color system is capable of showing 420 television lines or 210 optical line-pairs in both the horizontal and vertical orientation. The floor-mounted black and white monitors will show 500 television lines (250 line-pairs) horizontally and 450 television lines (225 line-pairs)

vertically. The VFA system is a standard 525 line system. This means that the number of horizontal scan lines is 525. Because of the spaces between the scan lines and the fact that a single line tends to show a Gaussian luminance profile, the number of television lines discernible is always less than the number of scan lines. Generally, in the vertical direction, the ratio of television lines to scan lines is about 0.7 to 0.95.

To summarize the resolution capability of the VFA system, the following are given:

1. The probe is diffraction-limited at 3.5 arc-minutes for point sources.

2. The color cockpit monitors will display 420 television lines in both the horizontal and vertical directions. With a field-of-view of approximately 36 degrees vertically and 48 degrees horizontally, this corresponds to a minimum spatial frequency of 5.83 cycles/degree vertically and 4.38 cycles/degree horizontally which is near the human peak response to contrast.

3. The operations black and white monitors will show 450 television lines vertically and 500 television lines horizontally, corresponding to spatial frequencies of 6.25 and 5.21 cycles/degree, respectively.

The preceding statements refer to _static_ resolution, i.e., when the image is not moving relative to the scanning device (camera tube). This is usually not the case in flight simulation and aircraft movements particularly yawing and pitching can impart high slew velocities to the images "seen" by the camera. When this happens, the resolution can be expected to decrease. This is due to the lag in the process of converting photons to electrons in the camera tube, the finite scan time. and the lag in the phosphorescent emissions of the monitor. All contribute to a smearing effect similar to that of motion pictures. It is not known at this time

what the rate of degradation is for the VFA system but resolution decreases
of 10 television lines per degree per second slew velocities are probable.

4.4.3 DEPTH OF FIELD

This is a term used to describe the ranges of distances within which
details are imaged with acceptable sharpness. At certain distances, the
details are sharpest, with sharpness decreasing with increasing or de-
creasing distance from the optimum. Like a camera lens that forms sharp
images of objects at certain ranges, the probe optics act similarly and it
is necessary to control the focus servo in order to form sharp images of
objects of interest.

The depth-of-field function is given in Table 4.4.3-1 for the probe
and in Figure 4.4.3-1 for the two model scales of 400/1 and 600/1. The
property results from the lens design and the range of travel of optical
components in the probe, and cannot be altered. Note that the closest
focus is about one inch which gives the nearest range to objects that can
be made distinct of 10.06 m (33 feet) at 400/1 scale, and 15.24 m (50 feet)
at 600/1 scale.

4.4.4 ABERRATIONS AND DISTORTION

The characteristics that are most apparent are some chromatic aberration
(false coloring of the images due to different colors being refracted dif-
ferently) and pincushion distortion. The latter may be thought of as a
slight increase in magnification of images as their angle off-axis increases.
If an image of a point should be located 10 degrees off-axis, the distortion
may cause it to show up at, say, 11 degrees. A linear grid will show out-
ward displacements with increasing angle off-axis and will appear with its
corners turned outward, hence the term "pincushion".

A photograph of a linear grid displayed on the monitor is shown in
Figure 4.4.4-1. Note the distortion at the edges of the field. Note also
the double lines at the picture edges. These are due to chromatic aberration.

TABLE 4.4.3-1

PROBE DEPTH OF FIELD LIMITS

FOCUS DISTANCE (cm)	NEAR FOCUS DISTANCE (cm)	FAR FOCUS DISTANCE (cm)
2.54	2.54	5.1
5.1	3.6	8.6
10.2	5.3	33.0
15.2	7.1	457.2
20.3	8.4	∞
25.4	9.7	∞
50.8	12.2	∞
76.2	12.2	∞

TABLE 4.4.3-1

PROBE DEPTH OF FIELD LIMITS

FOCUS DISTANCE (inches)	NEAR FOCUS DISTANCE (inches)	FAR FOCUS DISTANCE (inches)
1	1.0	2.0
2	1.4	3.4
4	2.1	13.0
6	2.8	180
8	3.3	∞
10	3.8	∞
20	4.8	∞
30	4.8	∞
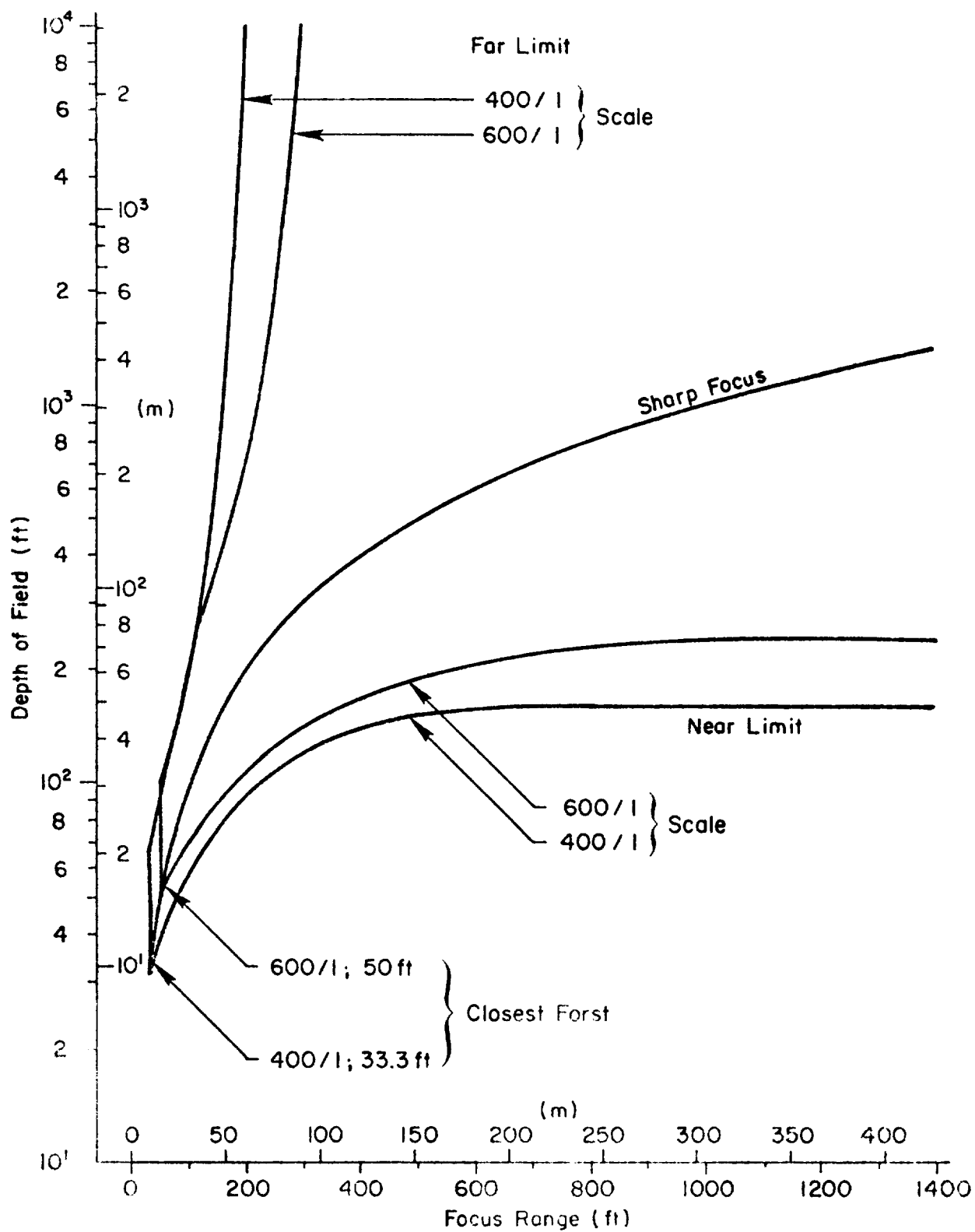
Figure 4.4.3-1: Depth of Field Functions
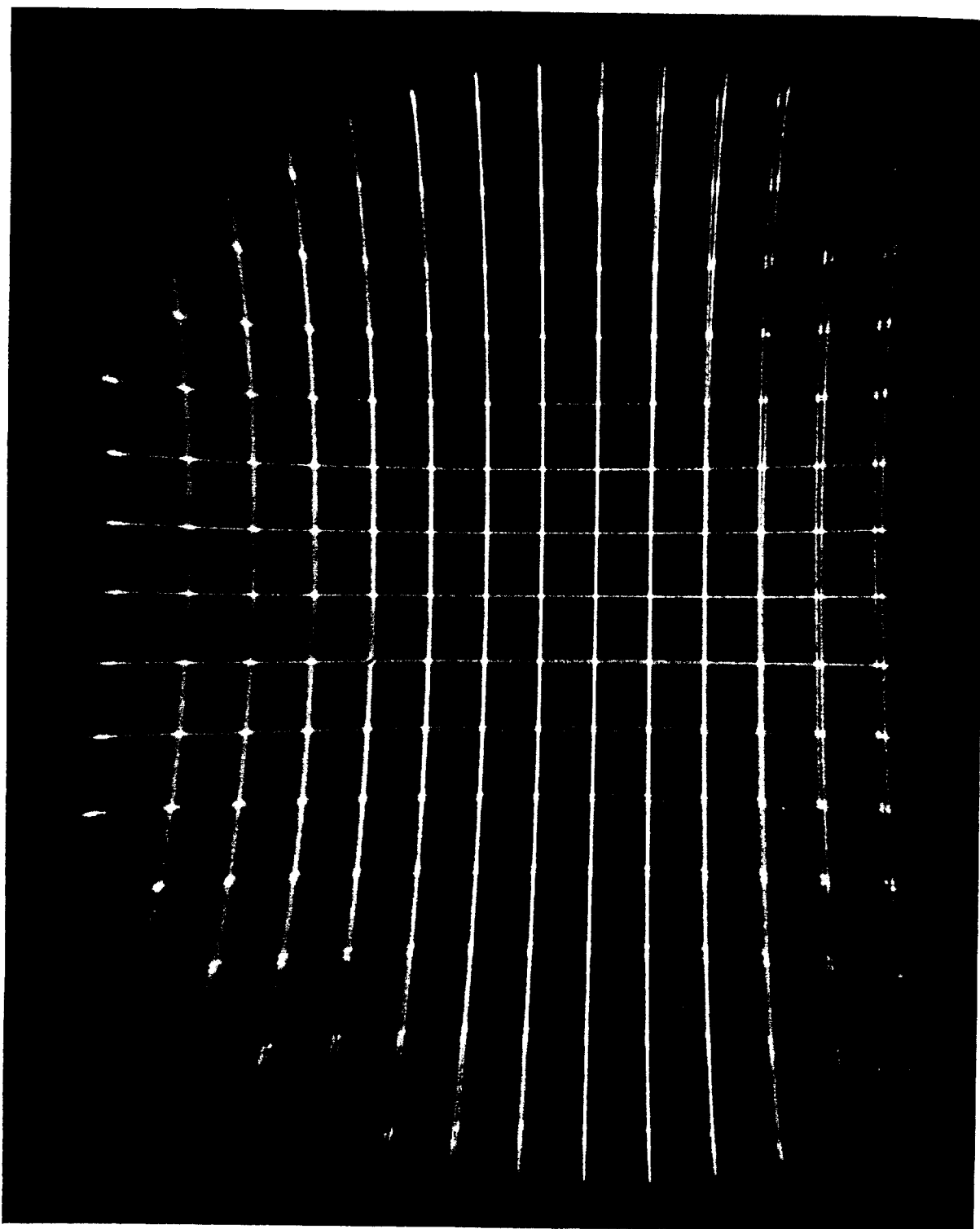
Figure 4.4.4-1: Collimating Lens System Distortion of a Linear Grid

A color photograph would show these lines to be two different colors; the breakdown of the white line as is seen in the center of the picture.

4.4.5 LIMITED VISIBILITY SIMULATION DEVICE

A device is incorporated in the television electronics that reduces image contrast. This feature can represent visibility conditions just under a low overcast where objects on the ground close to the aircraft are distinct and objects farther away on the ground (approaching the horizon) become less distinct until at some elevation angle the contrast is zero and no objects are visible. The device is driven by the probe pitch and roll servos' position feedbacks so that the haze appears earth-oriented. Roll capability of the device is limited to $\pm$ 50 degrees.

Two parameters are required from the user in order to activate the system. The first is the elevation angle of zero visibility, the second, the vertical angle through which the visibility will vary from zero to unrestricted. The ranges of each are:

1. Line of zero visibility is variable from the bottom to the top of the picture, i.e., $\pm$ 18.5 degrees.

2. Visibility transition zone is variable in height from 2.46 degrees to 12.3 degrees. The contrast reduction from picture contrast (bottom boundary) to the line of zero visibility (top boundary) is linear. Some of these details are shown in the sketch of Figure 4.4.5-1.

4.5 MONITORING AND CHECKOUT PROCEDURES

4.5.1 ON-LINE MONITORING

The operator's control station for the visual system contains devices for monitoring the image quality and the servosystem that controls its orientation. These devices consist of monochrome and color television

Line of Zero Visibility (variable from top to bottom ±18.5°)

Runway

Haze
(Zero Contrast)

Horizon

48°

37°

Transition Zone
(variable height
from 2.46° to 12.3°)
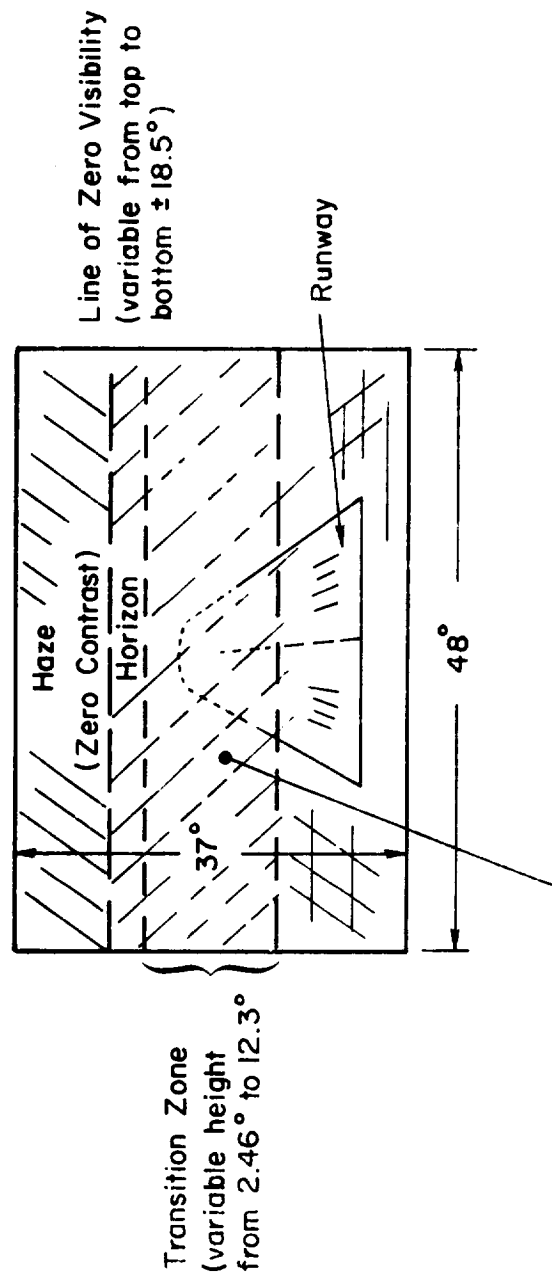
Transition zone of linearly varying contrast ranging
from 0 at top to normal picture contrast (Bottom)

Note: Picture contrast boundaries are driven by pitch and roll
angles to make haze appear earth-oriented.

Figure 4.4.5-1: Limited Visibility Simulation Device Parameters

monitors with auxiliary test equipment (oscilloscopes, etc.) mounted in a console with patch panels and jacks for quick access to all the important electrical pathways in the television system. Controls are located here for the local monitors, television electronics, auxiliary equipment such as the restricted visibility device, model lighting system, power supplies, and communications system.

The servosystem power controls are located here and the analog computer that interfaces to them. Besides an oscilloscope and wave analyzer, an eight-channel strip chart recorder is trunked to the computer which allows the on-line monitoring of critical display parameters. With the use of switching, all the important variables describing performance may be displayed, one axis at a time. The variables normally patched are:

1. Position command

2. Position follow-up potentiometer output

3. Derivative of position command (approximate velocity command)

4. Derivative of follow-up potentiometer output (approximate velocity feedback)

5. Position error (command minus feedback).

In the case of yaw, two command and two feedback signals (sawtooth waves) are required for the continuous servo. They are analogous to the sine and cosine of the command and feedback heading angles.

Although these signals are readily available for inspection during operation, any voltage on the analog computers may be displayed on request.

4.5.2 IMAGE QUALITY CHECKOUT

The television imaging system is checked on a daily basis. Four tests are made:

1. Linearity

   Using a standard linearity test chart placed before the camera,
   the television camera is adjusted so that the displayed target
   coincides with a grid generated by the television electronics.
   In this way, any distortion caused by the probe optics and
   camera tubes are compensated. This test and adjustment ensures
   that the correct field dimensions have been established and that
   the field is linear (i.e., free of distortion).

2. Video Level Adjust

   Using a black and white test target, the signal levels of red,
   blue, and green are set within prescribed tolerances for the
   darkest black and the brightest white.

3. Signal-to-noise level is checked for each channel

4. Monitor Checkout

   The cockpit color monitors are adjusted until the picture
   appears in natural color and luminance.

5. Static Resolution

   Using a standard Electronics Institute of America (EIA)
   resolution test chart, the number of television lines
   that can barely be recognized is observed for several
   areas in the field. This test not only checks the image
   quality of the camera, but also all operating television
   monitors.

4.5.3 SERVO SYSTEM SCALING

1. Gantry Translational Calibration

A two-point calibration is performed daily in which a zero and a non-zero voltage is applied to each translational servo. The resulting position of the gantry is measured using calibration markers on the ways and adjusted by setting biases and scale factors.

2. Probe Orientation Calibration

With an electronic grid superimposed on the picture and a test mirror fastened at one end of the model, the gantry is returned to its null (center) position. Zero voltage is applied to the probe rotational servos and alignment of the mirror with the center of the monitor (center crossline or optical axis) is checked. The probe is then rolled and the optical axis is further checked against the mirror. If the mirror appears to translate in a circular arc, the optical axis is not aligned with the probe roll axis and the optical elements will be realigned during maintenance unless the error is significant. Following optical axis alignment with the roll axis, roll, pitch, and yaw are calibrated with zero and non-zero commands using observations of the model mirror and horizon relative to the electronic grid. A two-point calibration is deemed sufficient for daily checks. The focus drive is not normally checked.

3. Computer Checks

When the hardware is placed under computer control, additional checks are performed. Generally, the minimum altitude, the runway heading, and zero lateral displacement relative to the approach boundary are read into the computer and centerline alignment is checked. If necessary, a lateral bias is introduced to "tune up" the alignment. Next, the probe is turned 90 degrees in yaw,

revealing the approach boundary. The alignment down the runway
may be checked. If the commands are read to move to the opposite
end of the runway, a two point calibration of runway length
is obtained. Height is checked using a mask placed on the colli-
mating lens face in the simulator cockpit. This mask usually
shows the runway sides for various heights, ranges to the threshold,
and lateral displacements. A visual check of probe placement
relative to a runway in three dimensions may be obtained by
comparing the displayed runway with the mask lines.

4. Dynamic Checks

As a measure of the linear characteristics, a SAFE frequency
response measurement is made every day. This technique is
described fully in Section 5 and will not be reiterated here.
The gain distribution of the driving sinusoids used for a
visual SAFE run, however, are different from that of a motion
SAFE analysis. The gain distribution used is shown in
Table 4.5.3-1.

TABLE 4.5.3-1

SAFE VISUAL FREQUENCY RESPONSE INPUT COMPONENT AMPLITUDES

COMPONENT FREQUENCY (rad/sec)	COMPONENT AMPLITUDE (NORMALIZED TO MAXIMUM)	
	TRANSLATION	ROTATION
0.218	1	1
0.327	-1	-1
0.545	-1	-1
0.873	1	1
1.31	1	1
1.96	-0.8	-1
3.27	0.4	1
4.36	0	-0.8
7.85	0	0.6
13.1	0	-0.4
19.6	0	0.2

REFERENCES

4-1   Sherr, Sol, _Fundamentals of Display System Design_, Wiley-Interscience, A Division of John Wiley & Sons, New York.

SECTION 5

S10 MOTION SYSTEM

5.1 HARDWARE

5.1.1 GENERAL DESCRIPTION OF HARDWARE

The motion system of the FSAA is a six-degree-of-freedom device
designed to impart rotational and translational movement to the cockpit.
Its most dramatic feature is the 30.5 m (100 ft) long track arrangement
that provides lateral motion. A gantry structure on wheels rides atop
these tracks and supports a platform on three screw jacks and two novel
pneumatic "equilibrators". The jacks provide vertical movement of the
platform and the equilibrators counterbalance the weight. A single
horizontal screw jack mounted on this platform drives an additional plat-
form which rides fore and aft on lathe-like ways. A relatively conventional
gimbal system forms the upper part of the device and carries the cockpit.
The six axes of motion (starting with the ground) are: lateral (Y),
vertical (Z), longitudinal (X), and finally the rotational gimbals are
arranged in the conventional order of yaw, pitch, and roll. All axes are
driven by electrical motor-generator combinations through devices such as
belts, timing chains, and toothed wheels. Rubber facing is used to reduce
backlash. A powered tracked carriage follows the lateral movement of the
gantry while carrying all the power and control cables to the cockpit and
driving devices. The rotational axes intersect at a common point which is
located in the symmetrical plane of the cockpit, 83.8 cm (33 inches) aft
of the instrument panel face and 45.7 cm (18 inches) up from the floor.
A schematic arrangement is shown in Figure 5.1.1-1.

Control of the motion base is aided by a complement of sensors con-
sisting of tachometers, follow-up potentiometers, rotary accelerometers,
and linear accelerometers. A sophisticated array of hardware-limiting
logic is included that is designed to prevent the hardware from reaching

OBSERVATION ROOM

CONTROL ROOM

LONGITUDINAL (X) AXIS

LATERAL DRIVE TRACTOR AND PIT

LOADING DOCK

LATERAL (Y) AXIS

COCKPIT

VERTICAL (Z) AXIS

EQUILIBRATOR PIT

YAW AXIS

COCKPIT DISPLAY ACCESS PLATFORM

PITCH AXIS

EQUILIBRATORS

VISUAL DISPLAY ENCLOSURE

GIMBAL CENTER

ROLL AXIS

CABLE CARRIER

POWER CABLES
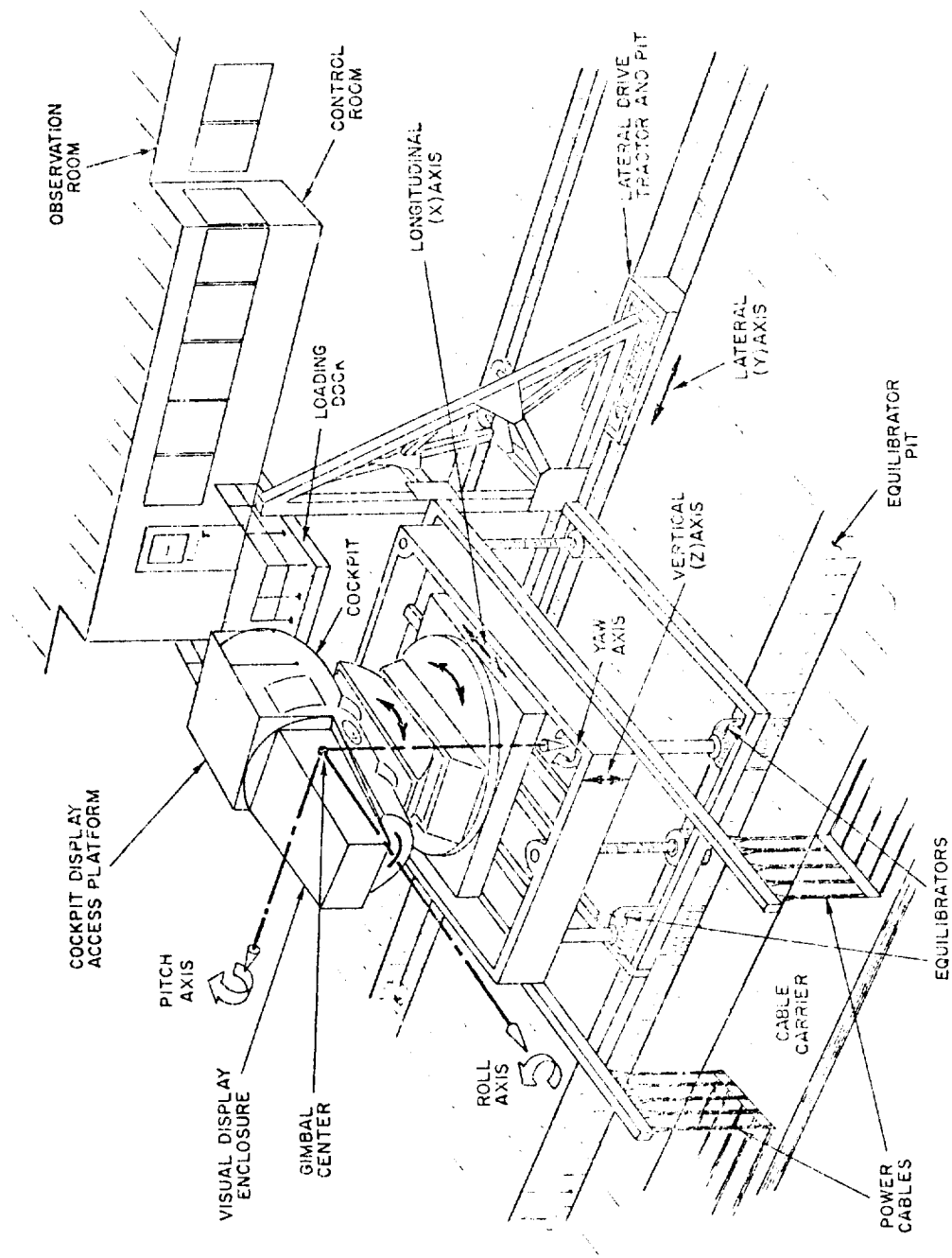
Figure 5.1.1-1: Schematic Arrangement of the S10 Motion System

operating conditions that could damage it. These are discussed more fully later.

Various control modes are incorporated into the drive electronics that facilitate the startup and shutdown procedures. These electronic units are separated from the computer but communicate with it. Besides providing control of the device, they incorporate many features that are part of the redundant safety system.

5.1.2 DIGITAL COMPUTER INTERFACE

A unit called the "drive rack" provides the interface between the digital computer and the motion system. It is physically located in the operator's control room and consists of monitoring and control equipment, operational amplifiers, and electrical networks. The primary functions of the drive rack are:

- To move the cab between the dock and center positions
- To minimize startup and shutdown transients

The drive rack has three hardware modes: dock, center position, and initial condition/operate. In the first two modes, the motion commands from the digital computer are not passed to the motion system. Under motion operator control, the drive rack moves the system to the dock or center position (the dock position is the position which aligns the cockpit with the loading dock permitting entrance or exit. It is not in the center position of the actuators.) In the initial condition/operate mode, computer commands are passed through the drive rack to the motion system.

A normal startup sequence is as follows:

1. Computer is in IC mode and drive rack is in dock mode as crew enters cab.

2. Motion operator puts drive rack in center position mode to move cab to center position.

3. After checking with the pilot and computer operator, the motion operator puts the drive rack in the IC/operate mode.

4. When the cab has stabilized in the IC position commanded by the computer, the operate button is enabled.

5. The motion operator pushes the operate button to put the computer into the operate mode.

6. When the run is terminated by the pilot, digital computer, or motion operator, the drive rack reverts to the center position mode and the computer to the IC mode.

7. For another run, the process is repeated from step 3.

Entering the hold mode of the computer reverts the motion system to center position, i.e., the motion system does not hold its last position.

5.1.3 PERFORMANCE LIMITS

The electrical drive trains impose several performance limits on the system. To protect the machinery from damage, a sophisticated array of sensors and shutdown devices are incorporated in the drive system to monitor the important performance parameters and automatically shut down the motors when acceptable limits are exceeded. It is important to know about these limitations to avoid unnecessary transients and shutdowns.

The most obvious limits are the maximum travel of each axis. These "hard" stops are softened through the use of hydraulic buffers, a ram device designed to produce acceptable decelerations from rated velocity. Before the buffers are encountered, however, reset switches are placed that shut down the motors.

The acceleration limits are more complicated because each motor has both temperature and current limitations. Exceeding these values would probably result in damage to the motors so thermal and magnetic protection devices are incorporated that, combined, have the properties of fuses, i.e.,

the devices shut off power to the motors when a current of a certain magnitude has occurred for a set time. A large current is tolerated for only a short time. In a direct-current motor, current is nearly proportional to output torque so the above limitations appear as a maximum torque and therefore an acceleration limitation.

As a backup to computer limiting, additional limits are incorporated into the electrical drive units. These are "parabolic limiters" which are designed to command maximum rated deceleration when velocity and position are such that this deceleration will stop the simulator just short of the reset switches.

The above limitations are summarized in Table 5.1.3-1 and Figures 5.1.3-1 through 5.1.3-3. The table lists the displacement, velocity, and acceleration limits. Phase-plane plots of these limits are given in Figure 5.1.3-1 that includes both hardware and software (BBEND Subroutine) limits. The software limits are described more fully in Section 5.2.2. Figures 5.1.3-2 and 5.1.3-3 show how the acceleration limits vary with time (assumes constant acceleration magnitude).

5.1.4 DYNAMIC RESPONSE

A servo design analysis which was carried out during the development of each motion servosystem led to their configuration as _velocity_ servos. The criterion for this selection was the suppression of unwanted load accelerations. The design analysis revealed that the dominant damping ratios and natural frequencies of a velocity system were higher than those for a high-gain position system. Also, ringing of the lightly damped structure could be expected to be less when the servos were configured as velocity devices. Tests bore out these hypotheses and the velocity configuration was finally selected for its ability to produce smoother responses. Thus the digital computer command is velocity in all axes.

The dynamic characteristic of most concern to the researcher is the frequency response of the system. The frequency response was measured

TABLE 5.1.3-1

MOTION LIMITS

PARAMETER AXIS	DISPLACEMENT [1]	VELOCITY [2]	ACCELERATION [3]
ROLL Φ	$\pm$ 0.663 rad	$\pm$ 1.75 rad/sec	$\pm$ 2.09 rad/sec^2
PITCH Θ	$\pm$ 0.349 rad	$\pm$ 1.01 rad/sec	$\pm$ 2.62 rad/sec^2
YAW Ψ	$\pm$ 0.436 rad	$\pm$ 0.90 rad/sec	$\pm$ 1.68 rad/sec^2
LONGITUDINAL X	$\pm$ 1.0 m	$\pm$ 2.1 m/sec	$\pm$ 2.4 m/sec^2
LATERAL Y	$\pm$ 12.2 m	$\pm$ 8.7 m/sec	$\pm$ 2.4 m/sec^2 [4]
VERTICAL Z	$\pm$ 1.3 m	$\pm$ 2.6 m/sec	$\pm$ 3.7 m/sec^2

[1] Maximum displacement allowed by the parabolic limiter.

[2] Maximum velocity reached under a maximum acceleration
starting from rest at one end of the available travel and
driving into the parabolic limiter at the other end.

[3] Maximum instantaneous acceleration.

[4] Track rubber damage is likely at these values.

TABLE 5.1.3-1

MOTION LIMITS

PARAMETER / AXIS	DISPLACEMENT [1]	VELOCITY [2]	ACCELERATION [3]
ROLL ϕ	$\pm$ 0.663 rad	$\pm$ 1.75 rad/sec	$\pm$ 2.09 rad/sec^2
PITCH θ	$\pm$ 0.349 rad	$\pm$ 1.01 rad/sec	$\pm$ 2.62 rad/sec^2
YAW Ψ	$\pm$ 0.436 rad	$\pm$ 0.90 rad/sec	$\pm$ 1.68 rad/sec^2
LONGITUDINAL X	$\pm$ 3.45 ft	$\pm$ 7.0 ft/sec	$\pm$ 8.0 ft/sec^2
LATERAL Y	$\pm$ 40 ft	$\pm$ 28.6 ft/sec	$\pm$ 8.0 ft/sec^2 [3][4]
VERTICAL Z	$\pm$ 4.2 ft	$\pm$ 8.6 ft/sec	$\pm$ 12.0 ft/sec^2

[1] Maximum displacement allowed by the parabolic limiter.

[2] Maximum velocity reached under a maximum acceleration starting from rest at one end of the available travel and driving into the parabolic limiter at the other end.

[3] Maximum instantaneous acceleration.

[4] Track rubber damage is likely at these values.
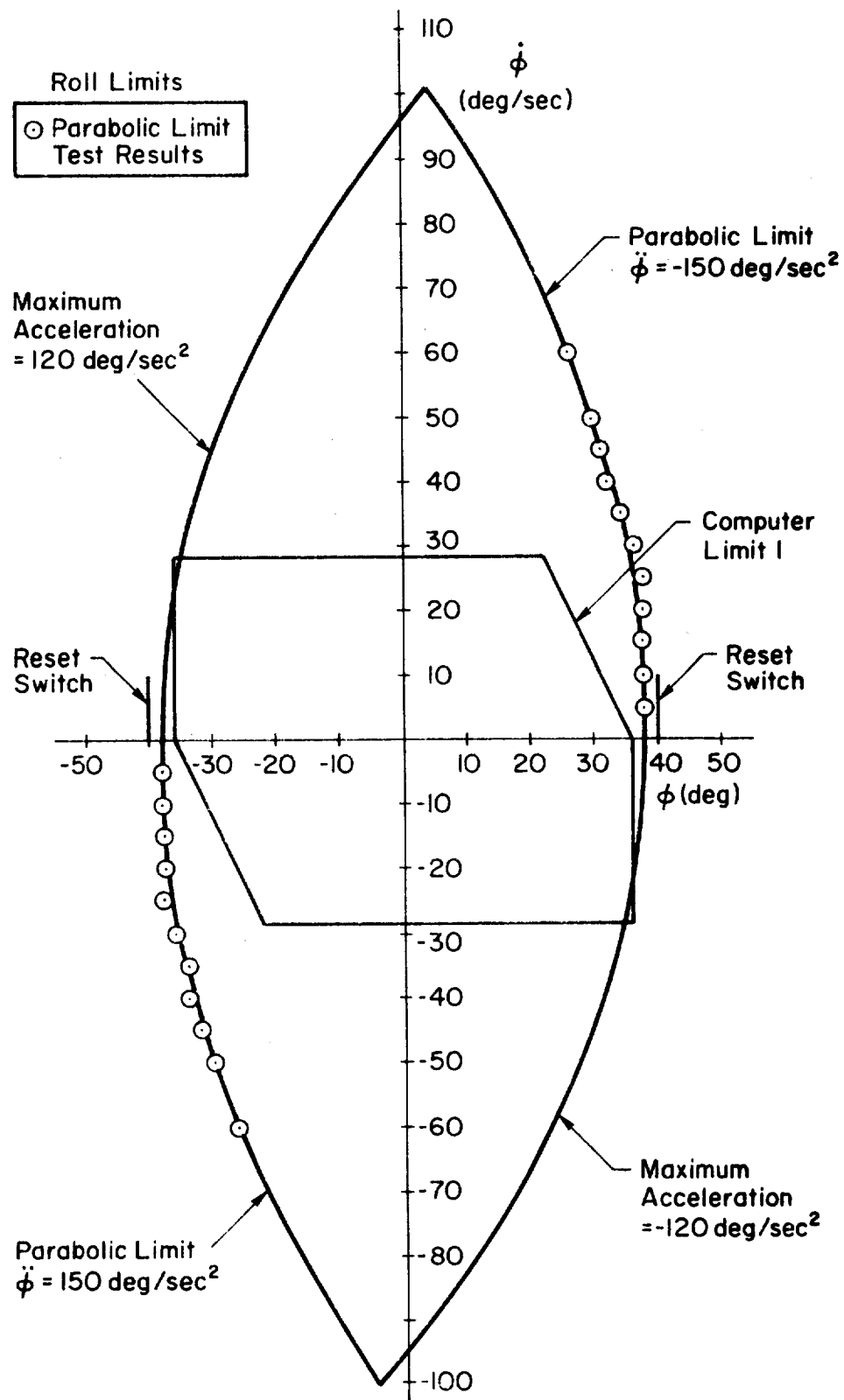
Figure 5.1.3-1a: Phase Plane Plots of Motion Limits

V-8
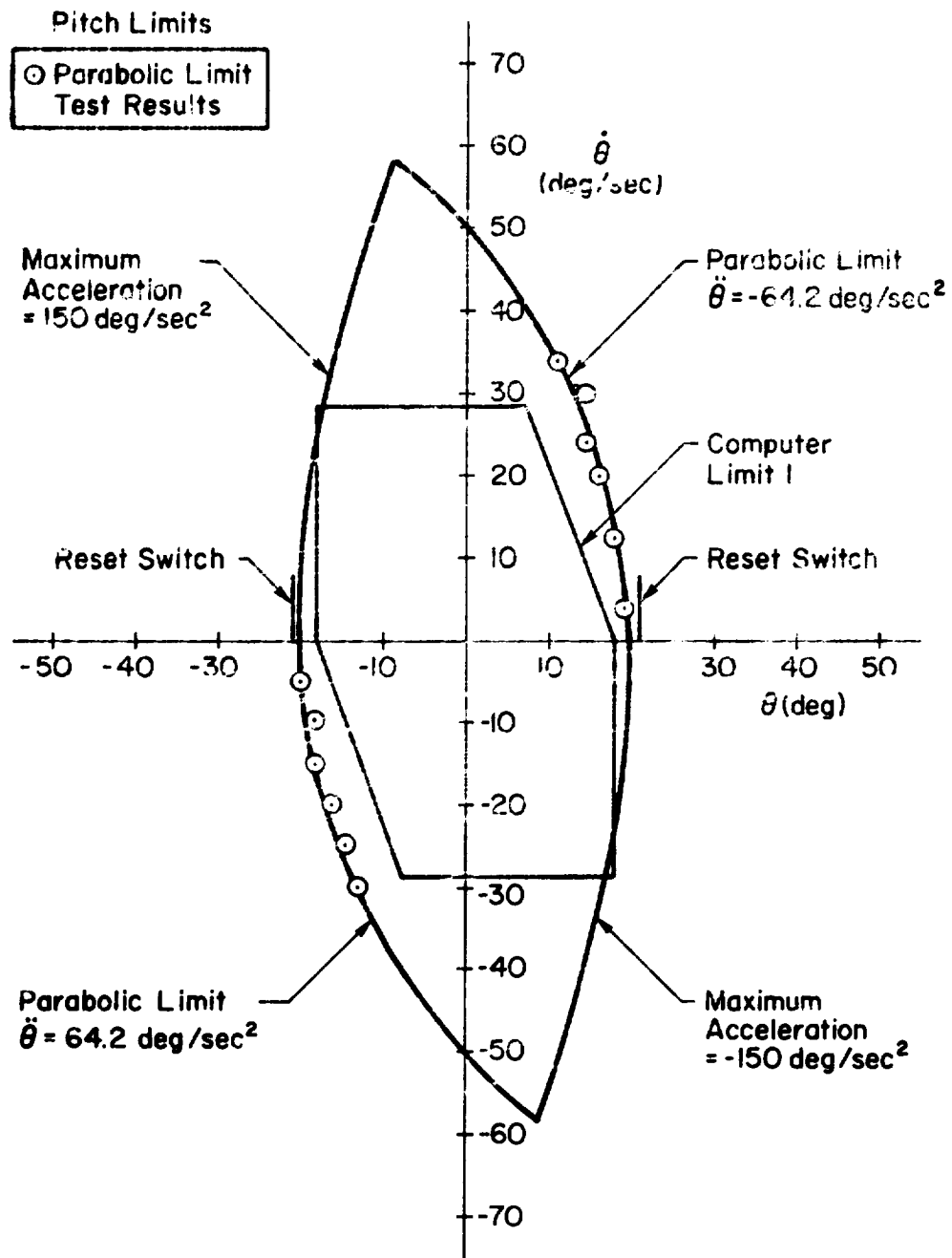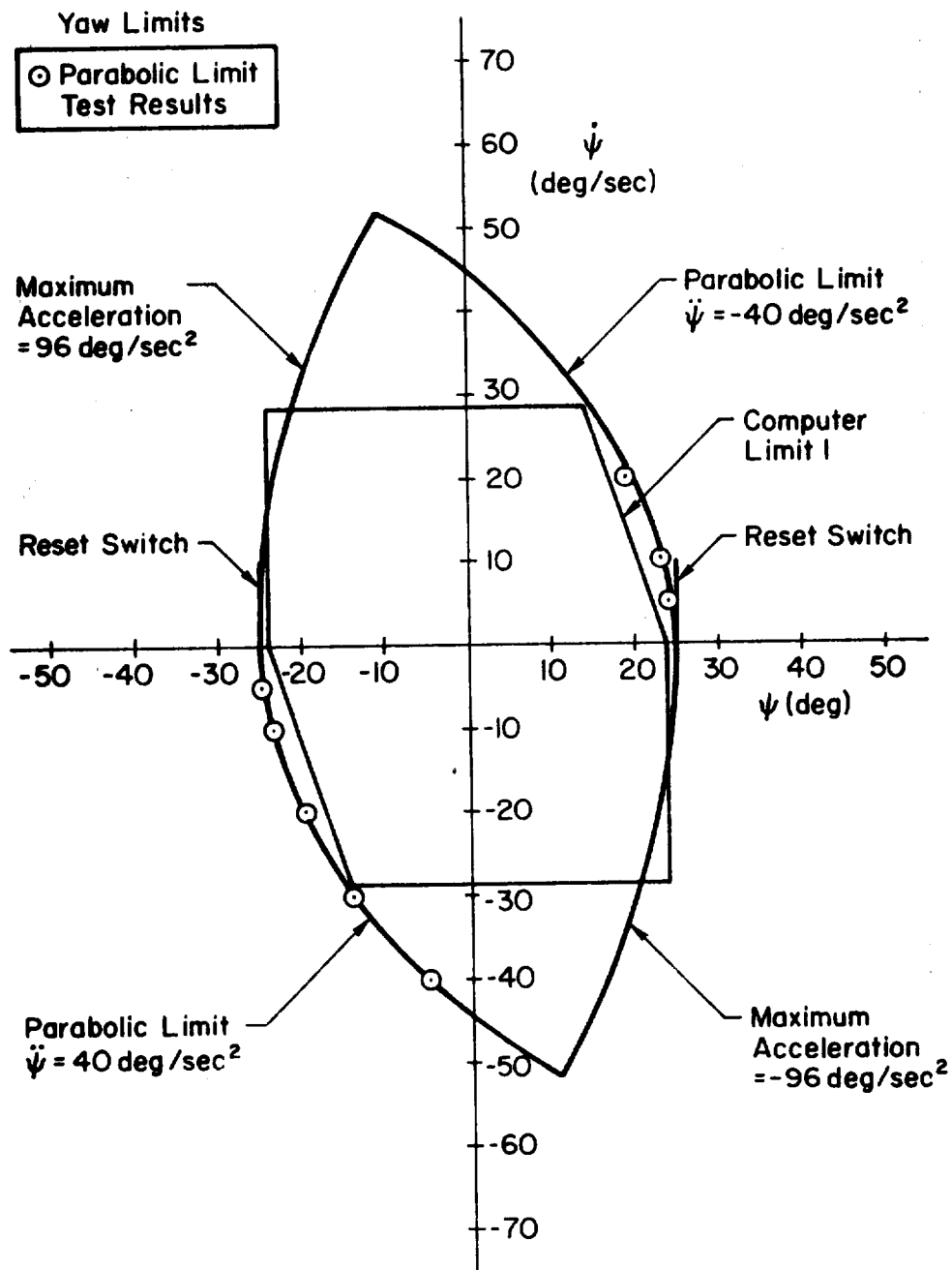
Figure 5.1.3-1b

Figure 5.1.3-1c
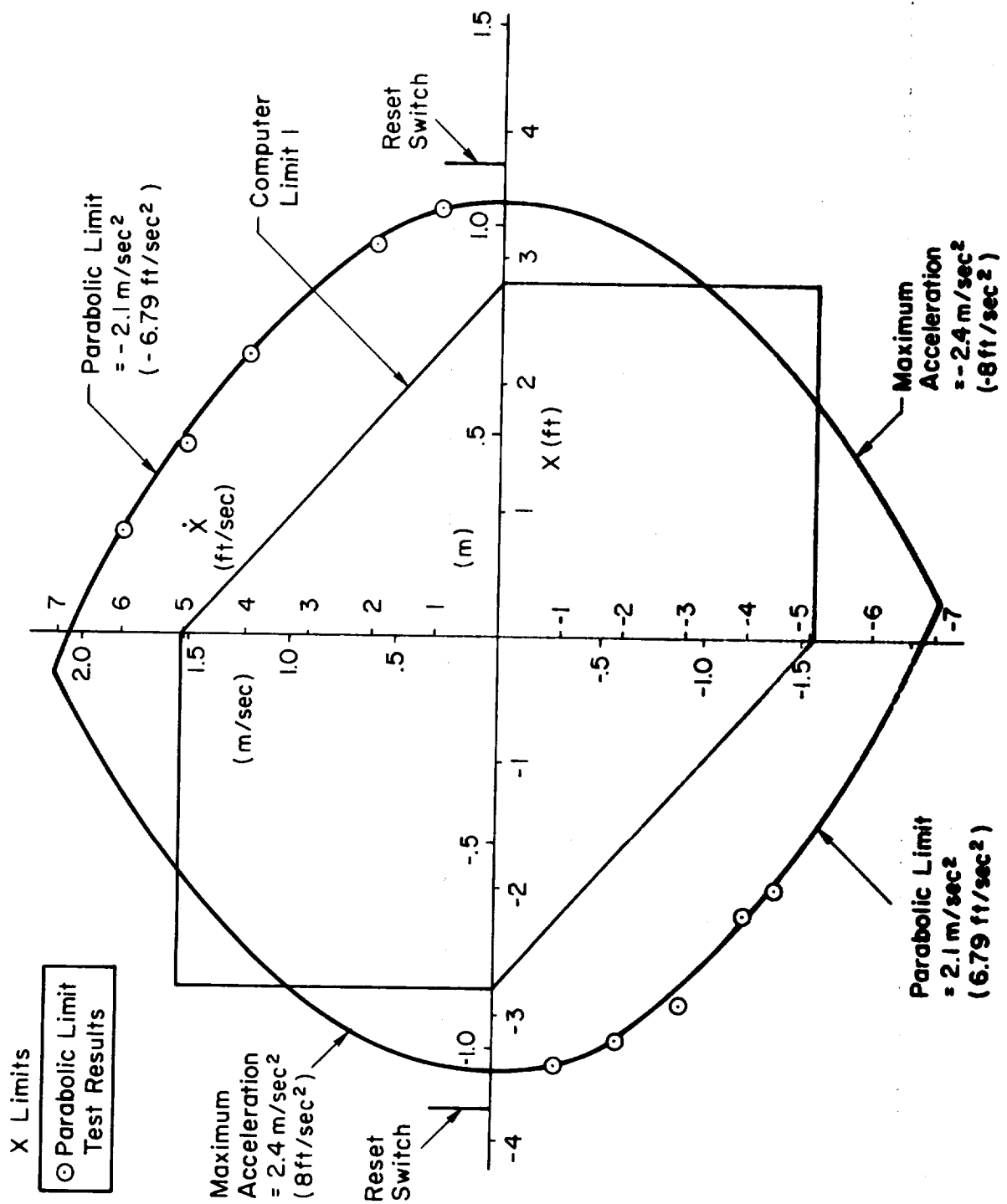
Figure 5.1.3-1d

Figure 5.1.3-1e

V-12
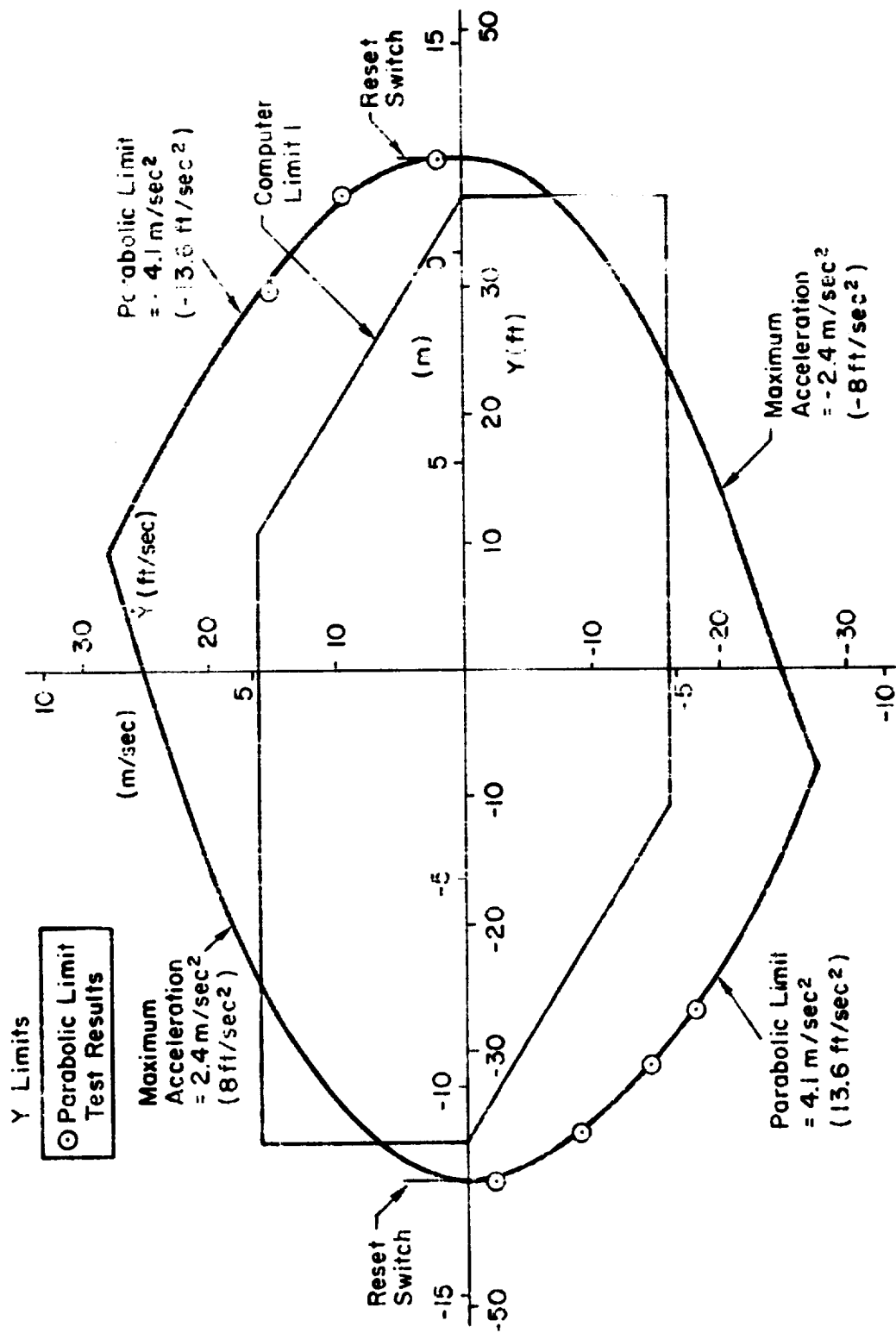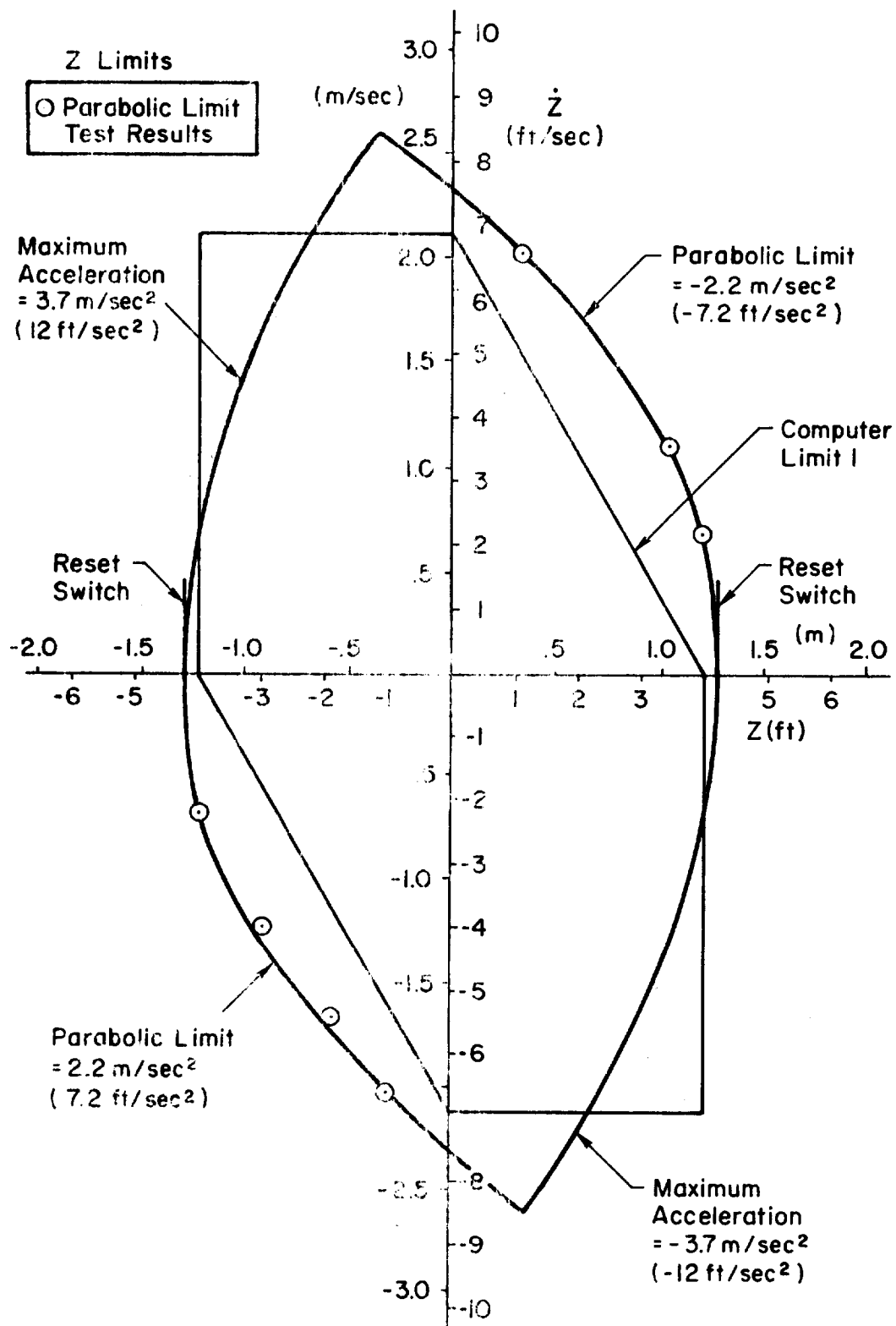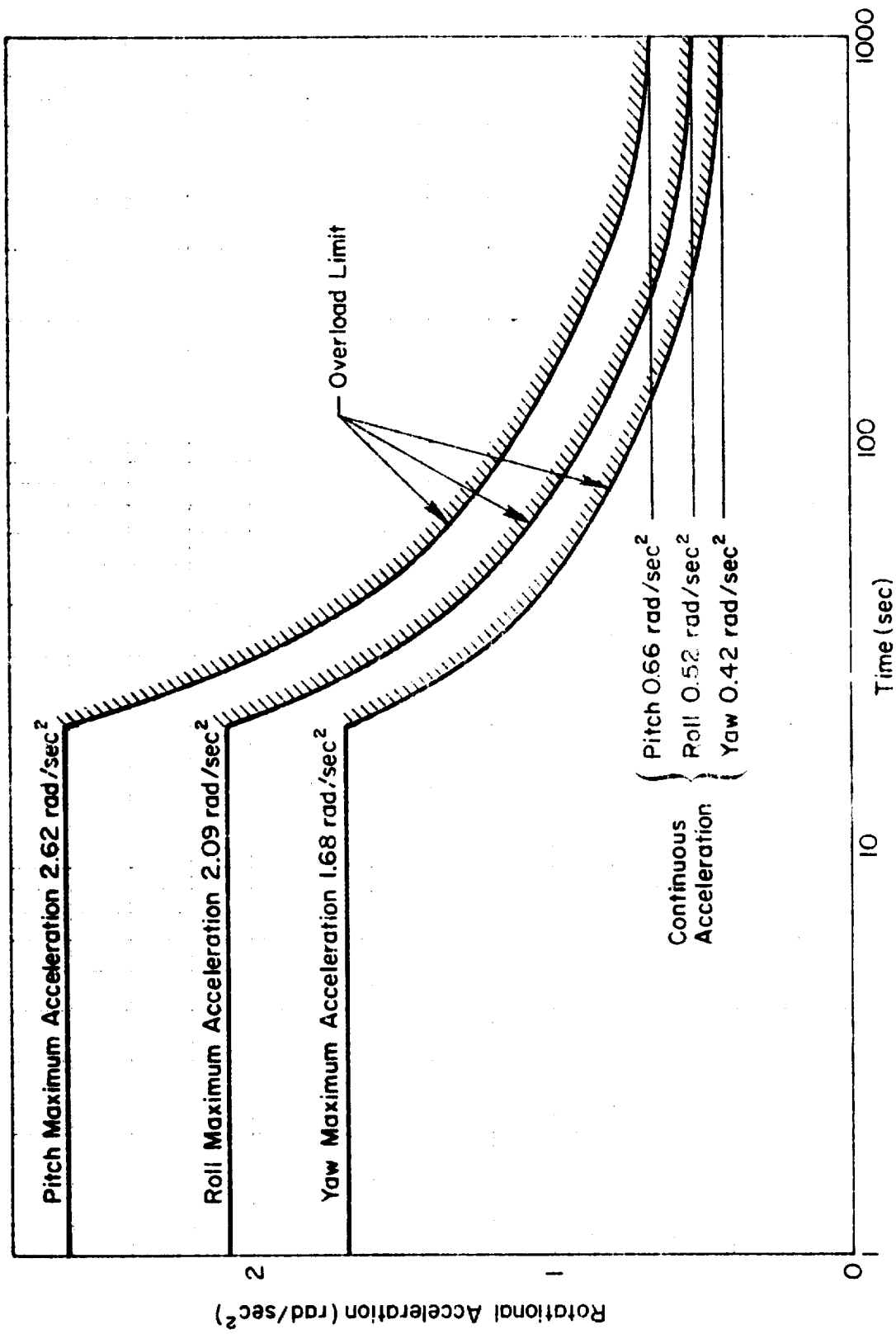
Figure 5.1.5-1f

Figure 5.1.3-2: Rotary Acceleration Limits.
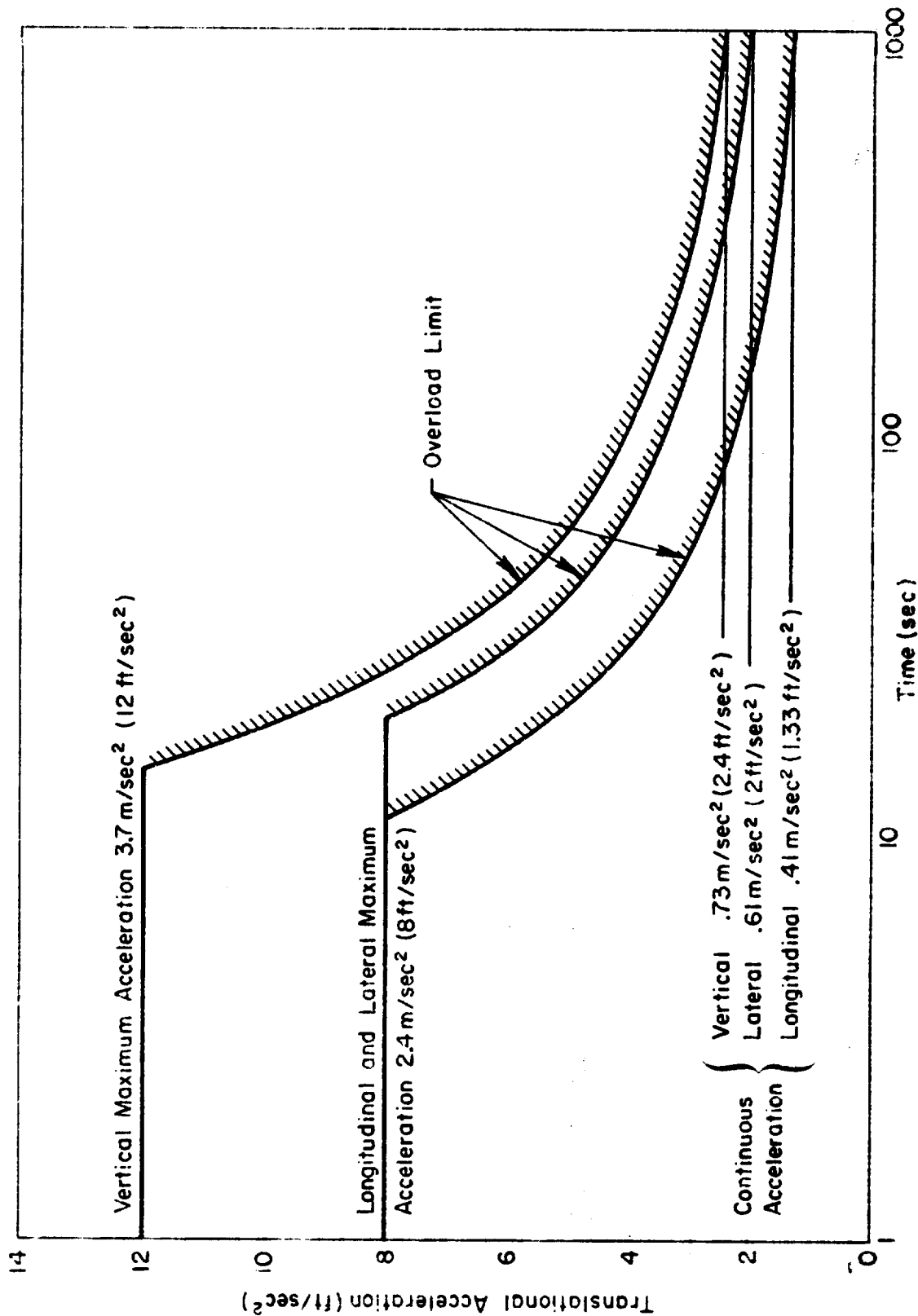
Figure 5.1.3-3: Translational Acceleration limits.

Vertical Maximum Acceleration 3.7 m/sec² (12 ft/sec²)

Longitudinal and Lateral Maximum Acceleration 2.4 m/sec² (8 ft/sec²)

Overload Limit

Continuous Acceleration
{
Vertical .73 m/sec² (2.4 ft/sec²)
Lateral .61 m/sec² (2 ft/sec²)
Longitudinal .41 m/sec² (1.33 ft/sec²)
}

Time (sec)

Transitional Acceleration (ft/sec²)

V-15

with the SAFE Routine described in Section 5.3.2. The results are shown in Figure 5.1.4-1 and the normalized amplitude distribution of the input sinusoids are listed in Table 5.1.4-1. The response data are considered valid only in the range of amplitudes unaffected by threshold or limiting effects. Table 5.1.4-2 lists the parameter values for a second order model fit to these data where the model is represented by:

$$G_n(jw) = \frac{K_n}{s^2 + 2\zeta_n \omega_n s + \omega_n^2}$$

Another characteristic of possible concern is the velocity threshold. Because of inherent real properties of the motors and load (simulator cockpit and supporting structure) such as friction and backlash, a finite velocity command is required before the motors will begin to move the simulator. These thresholds are listed in Table 5.1.4-3 for ramp velocity inputs.

5.2 SOFTWARE

5.2.1 GENERAL DESCRIPTION OF SOFTWARE

The digital computer commands which drive the motion system are generated in the BBEND Subroutine which is part of the BASIC software. The inputs to this subroutine are the cockpit motions of the simulated aircraft. The outputs are velocity commands to the motion base. The angular inputs are angular acceleration components $(\dot{p}_B, \dot{q}_B, \dot{r}_B)$ of the simulated aircraft in body axes. The linear inputs are specific forces at the cockpit (A_{XP}, A_{YP}, A_{ZP}) again in body axes. Specific force means the observed acceleration that an accelerometer would measure. Specific force and true acceleration differ by the component of gravity in that direction.

The remainder of this subsection is a discussion of the general drive logic. The discussion starts with the drive logic for vertical because it is the simplest. Similar logic is used for yaw. The next subject is the coordinated logic for the longitudinal plane (pitch and longitudinal). Similar logic is used for the lateral plane (roll and lateral).
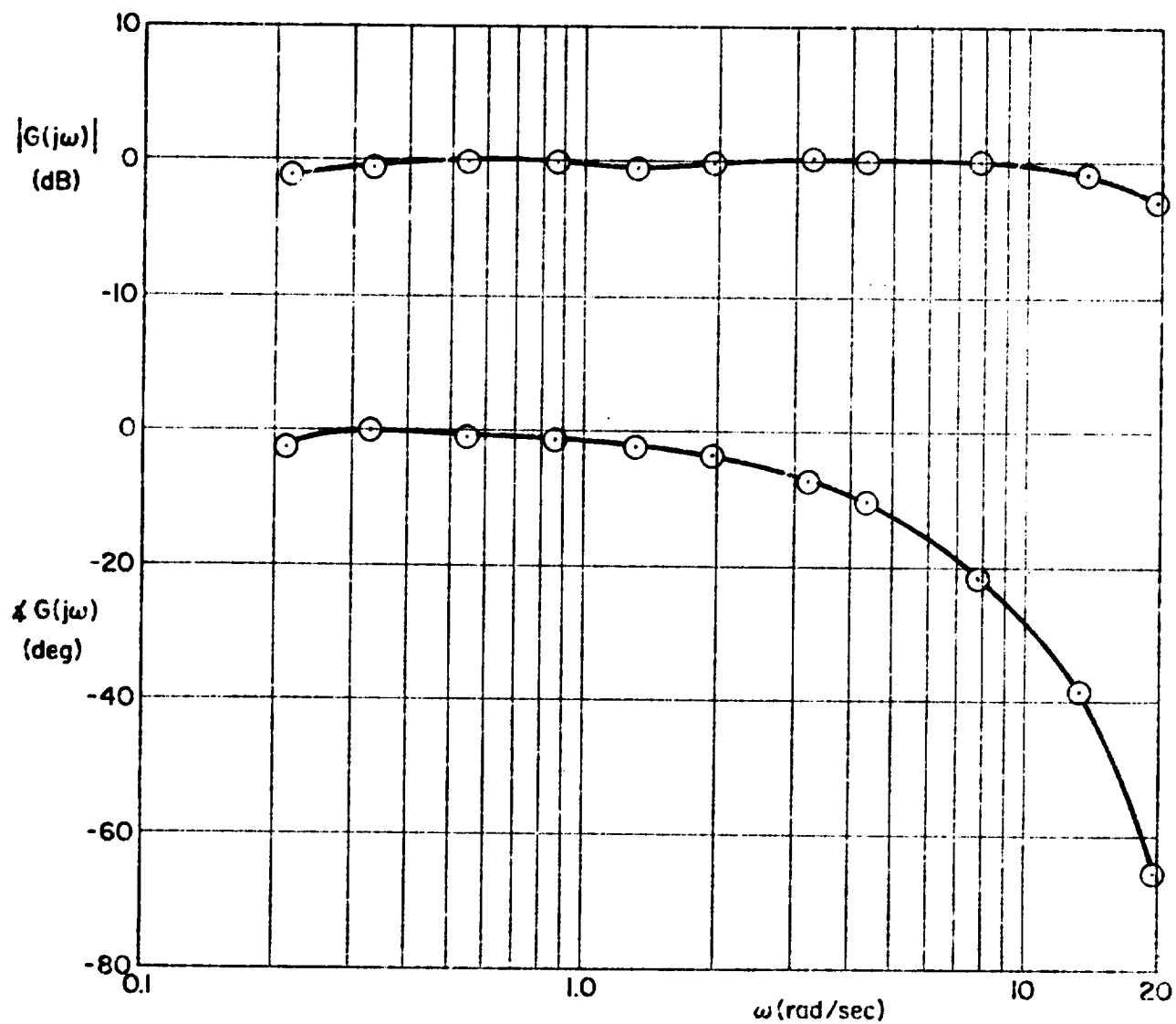
Figure 5.1.4-1:   SAFE Frequency Responses for the S10 Motion System.
ROLL

V-17
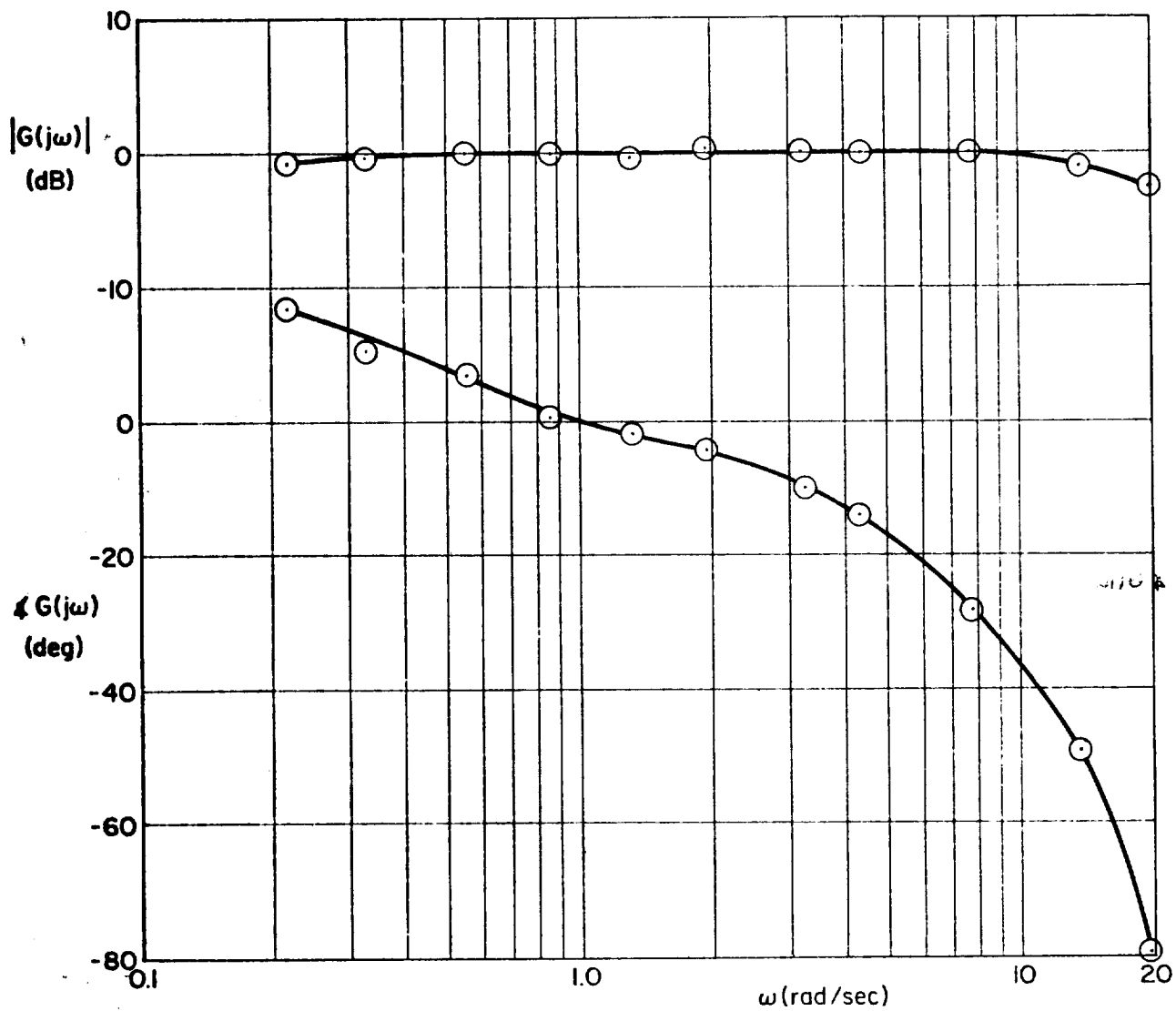
Figure 5.1.4-1

PITCH

V-18

Figure 5.1.4-1

YAW

V-19
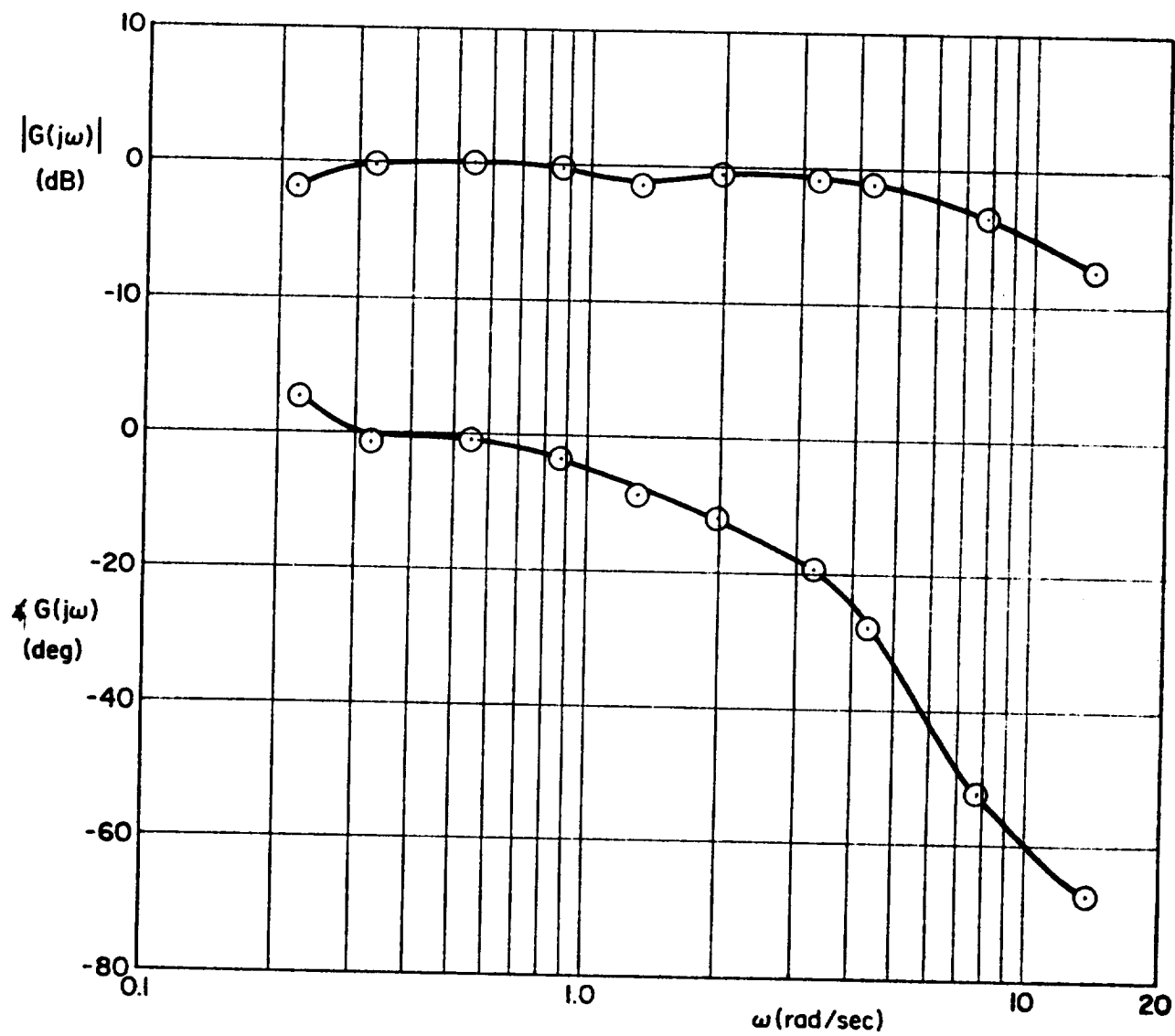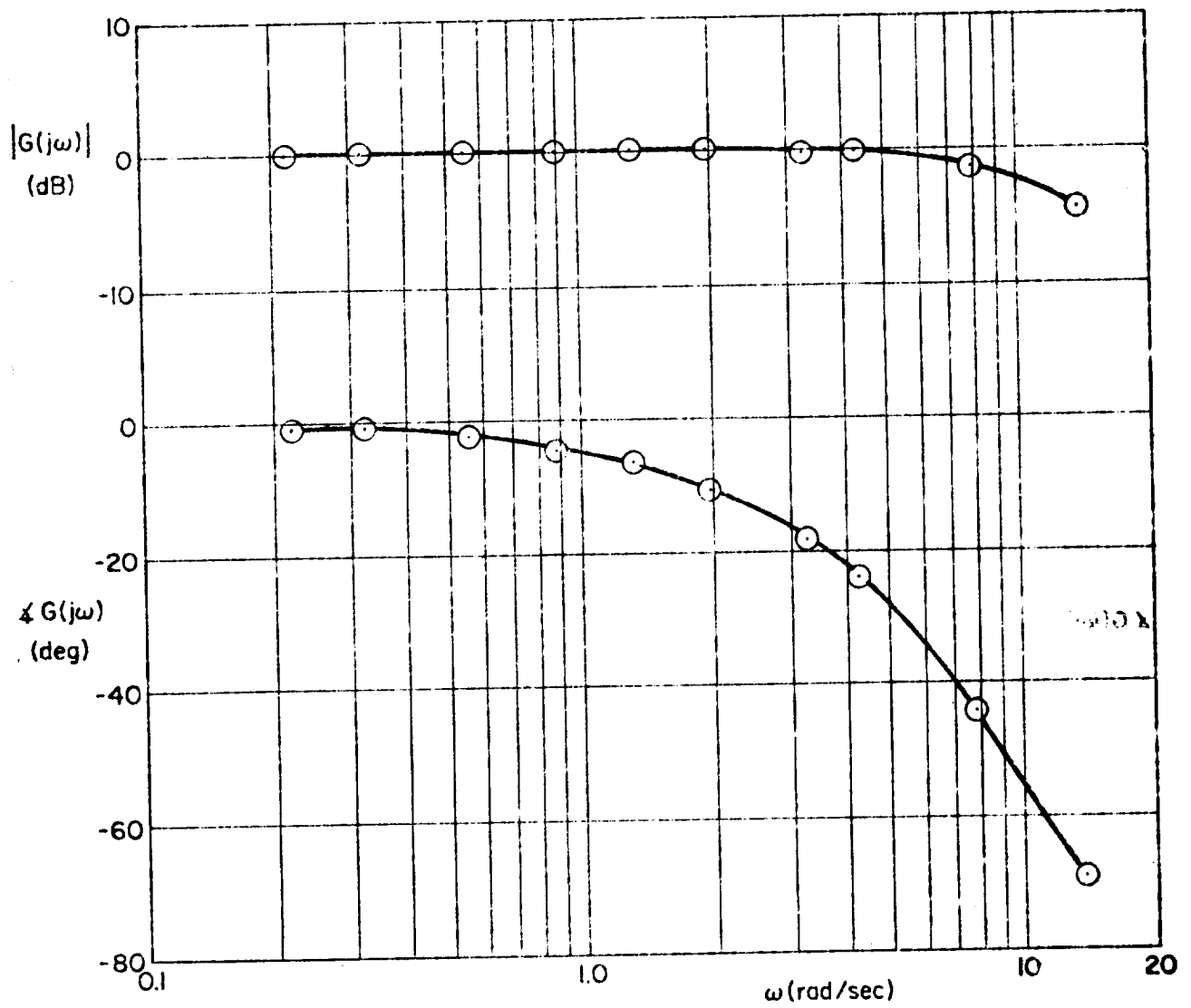
Figure 5.1.4-1

LONGITUDINAL

V-20
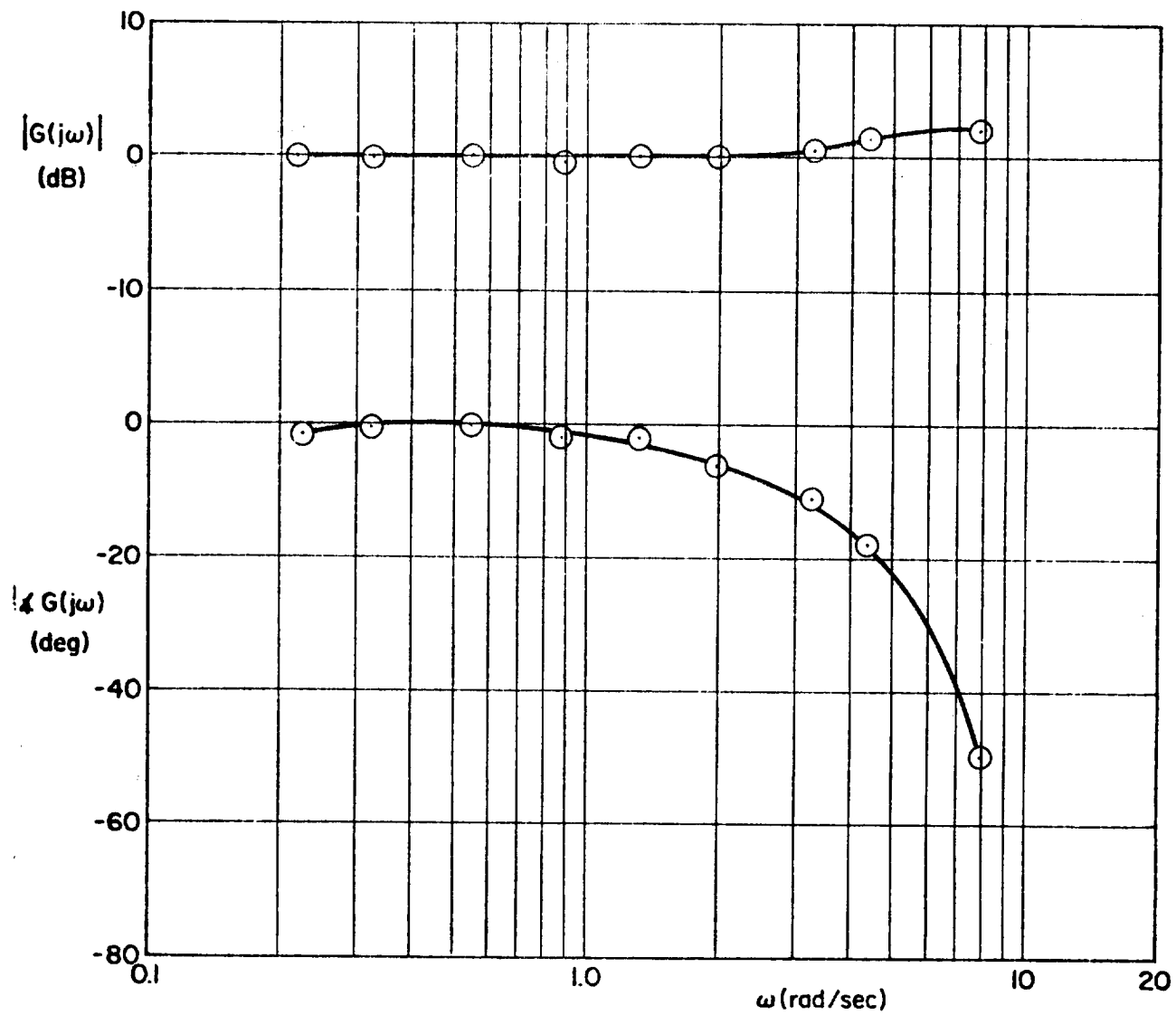
Figure 5.1.4-1

LATERAL

V-21
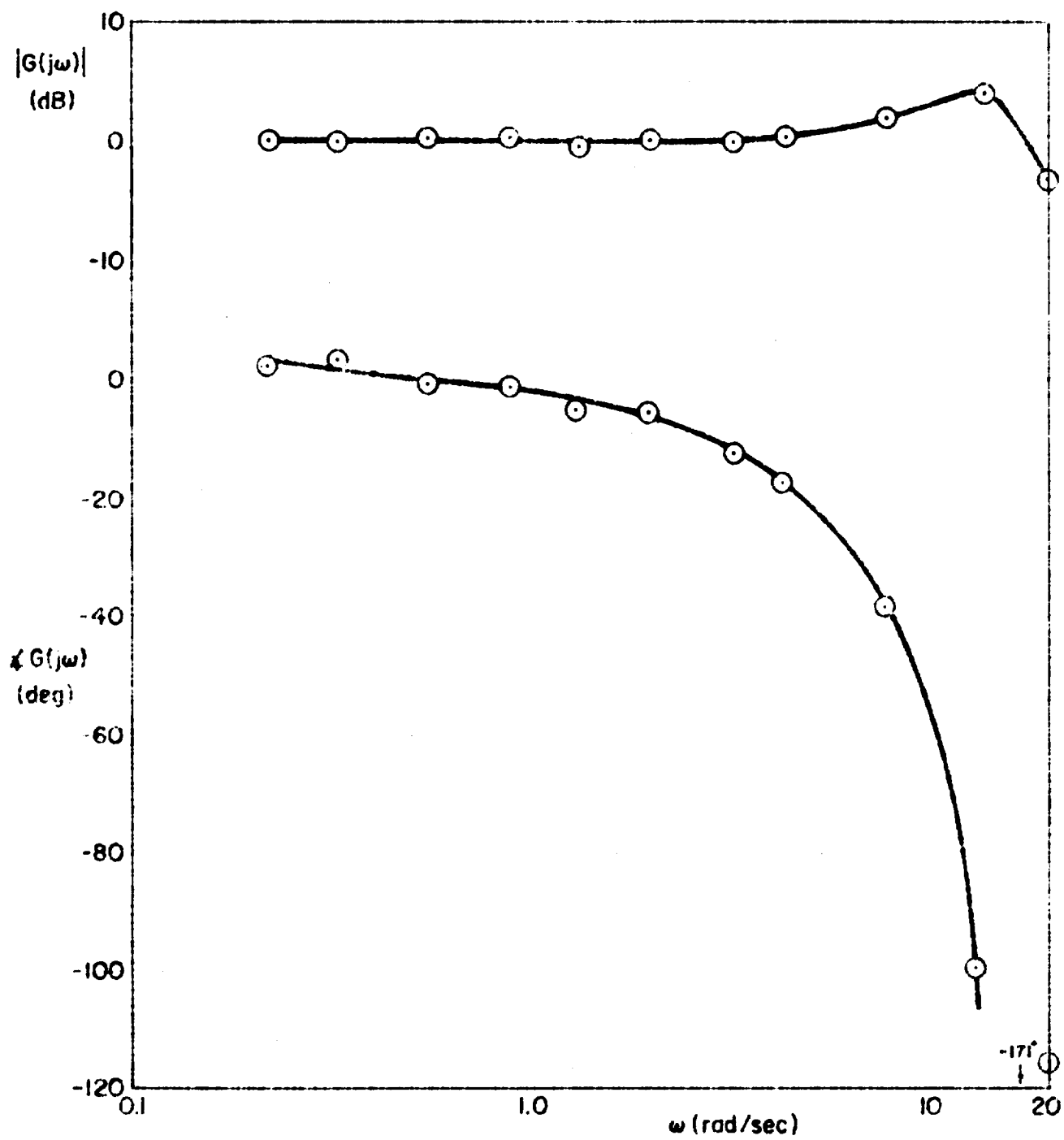
Figure 5.1.4-1

VERTICAL

V-22

TABLE 5.1.4-1

SAFE MOTION SYSTEM FREQUENCY RESPONSE INPUT COMPONENT AMPLITUDES

COMPONENT FREQUENCY rad/sec	COMPONENT AMPLITUDE (NORMALIZED TO MAXIMUM)	
	ROLL, PITCH, YAW, LONGITUDINAL, VERTICAL	LATERAL
0.218	1.0	1.0
0.327	-1.0	-1.0
0.545	-1.0	-1.0
0.873	1.0	1.0
1.31	1.0	1.0
1.96	-1.0	-1.0
3.27	-1.0	-0.8
4.36	0.8	0.6
7.85	0.6	0.4
13.1	-0.4	0
19.6	-0.2	0

TABLE 5.1.4-2

TABLE OF PARAMETERS FOR A SECOND ORDER MODEL FIT
TO THE FREQUENCY RESPONSE DATA

AXIS (n) PARAMETER	ROLL (φ)	PITCH (θ)	YAW (ψ)	LONG. (X)	LAT. (Y)	VERT. (Z)
K_n	0.96	0.97	0.95	1.01	1.03	0.96
ω_n (rad/sec)	28.49	21.00	36.31	18.77	11.17	12.44
ζ_n	0.76	0.64	2.58	1.09	0.40	0.24

TABLE 5.1.4-3

VELOCITY THRESHOLDS FOR RAMP INPUTS

Values of Command Velocity where
Movement is First Detected

AXIS	THRESHOLD
Roll	$+ 0.25$ $- 1.25$ deg/sec
Pitch	$+ 0.40$ $- 0.08$ deg/sec
Yaw	$+ 0.50$ $- 1.50$ deg/sec
Longitudinal	$+ 0.61$ $- 2.1$ cm/sec
Lateral	Less than ± 0.9 cm/sec
Vertical	$+ 3.1$ $+ 1.5$ cm/sec

TABLE 5.1.4-3

VELOCITY THRESHOLDS FOR RAMP INPUTS

Values of Command Velocity where
Movement is First Detected

AXIS	THRESHOLD
Roll	+ 0.25 - 1.25 deg/sec
Pitch	+ 0.40 - 0.08 deg/sec
Yaw	+ 0.50 - 1.50 deg/sec
Longitudinal	+ 0.02 - 0.07 ft/sec
Lateral	Less than ± 0.03 ft/sec
Vertical	+ 0.1 + 0.05 ft/sec

An overview of the drive logic for vertical is shown in Figure 5.2.1-1. The input quantity $A_{Zp} + g \cos \varphi \cos \theta$ is the vertical component of specific force summed with the body axis component of gravity*. Following the diagram, one sees a gain followed by a simple clipping-type limiter. The gain allows scaling of the vertical motion cues. The limiter prevents the logic from commanding excessive vertical accelerations that might reset the motion system. Following the limiter are two second-order high-pass filters that perform the basic attenuation function. The second of these is combined with an integration to give a washed-out velocity in body axes. The transform to earth-fixed space then converts the velocity to the vertical axis of the simulator, including the velocity components of the other two body axes. Another limiter follows that in essence reduces the velocity command to zero as the position limits are approached.

The final portion of the logic is recognized as a position drift control circuit with simple position limiting, bias, and an end-of-travel limiter that simply does not allow driving beyond the software position limit. All the limiters are fully discussed in Section 5.2.2.

The drive logic for yaw is identical in form except for the axis transformation. The transformation for all angular velocities includes the conversion from body angular rates to Euler angle rates.

Figure 5.2.1-2 is the overview diagram for the longitudinal and pitch axes. The reason for the combining of these axes into a single diagram is the fact that steady state longitudinal force simulation is accomplished by a mechanism called "residual tilt". With this technique the cockpit is pitched to an angle where the longitudinal component of gravity is equal to the simulated specific force. This requires a low-frequency crossfeed from the longitudinal axis to the pitch axis and with this interaction both axes should be discussed together.

A similar argument may be made for the lateral plane, i.e., roll and lateral (side force). The lateral logic is, however, identical in structure to the longitudinal and therefore is not discussed.

---

* The purpose of the gravity term is to bias the A_{Zp} which is equal to $- g \cos \varphi \cos \theta$ for steady level flight. The term will, however, introduce transients when the aircraft's Euler angles φ and θ pass through plus or minus 90 degrees.

VERTICAL LIFT

HARDWARE

LOAD
MOTOR
AND
POT

SOFTWARE

VELOCITY

STEPPER
DRIVER
LIMITING

CONTROL
LAW
GAIN

VERTICAL
VELOCITY
REF.

FORCE
FEEDBACK

COMMAND

HIGH-
PASS
LIMITING

EARTH-FIXED
SPACE

COMMAND TO
EARTH-FIXED
SPACE

VELOCITY
FORWARD
LOOP

FEEDBACK GAIN
VELOCITY
COMMAND
FORWARD LOOP

POSITION

STICK
POSITION
FILTERS

STICK
VELOCITY
FILTERS

STICK
GAIN

CONTROL
STICK

FUNCTIONAL BLOCK
DIAGRAM HELP VERTICAL
(2)

V-28

Following the longitudinal diagram of Figure 5.2.1-2 it is seen that the logic for either the pitch or longitudinal axis closely resembles that for the vertical axis. The only difference is the crossfeed between pitch and longitudinal. The residual tilt crossfeed is from longitudinal to pitch. Although the program has two residual tilt options, they are fundamentally the same in that both:

- Low pass filter the longitudinal input A_{X_P}

- Produce a steady state pitch increment to simulate a steady state A_{X_P}.

The crossfeed from pitch to longitudinal is strictly to convert from body axes specific force to earth axes acceleration. Considering only pitch and longitudinal motion, one would have:

$$\ddot{X} = A_{X_P} - g \sin \theta$$

or as it is mechanized in the computer

$$\dot{X} = \int A_{X_P} dt - \int g \sin \theta \, dt$$

This equation simply calculates the earth-fixed longitudinal acceleration from A_{X_P} and θ alone under the assumption that the A_{X_P} term rotates through small angles and that the body axis vertical acceleration is $-g$.

5.2.2 DETAILED DESCRIPTION OF SOFTWARE

This subsection is a detailed description of the motion system drive logic, specifically the BBEND Subroutine. The heart of this description is the block diagrams of Figure 5.2.2-1. The remainder of this subsection is largely an elaboration of features indicated in this figure.

All the computations indicated in Figure 5.2.2-1 are done in the BBEND Subroutine with the exception of the blocks to the far right labeled FSAA. These represent the dynamics of the motion base with respect to a velocity command input and a displacement output. These dynamics are
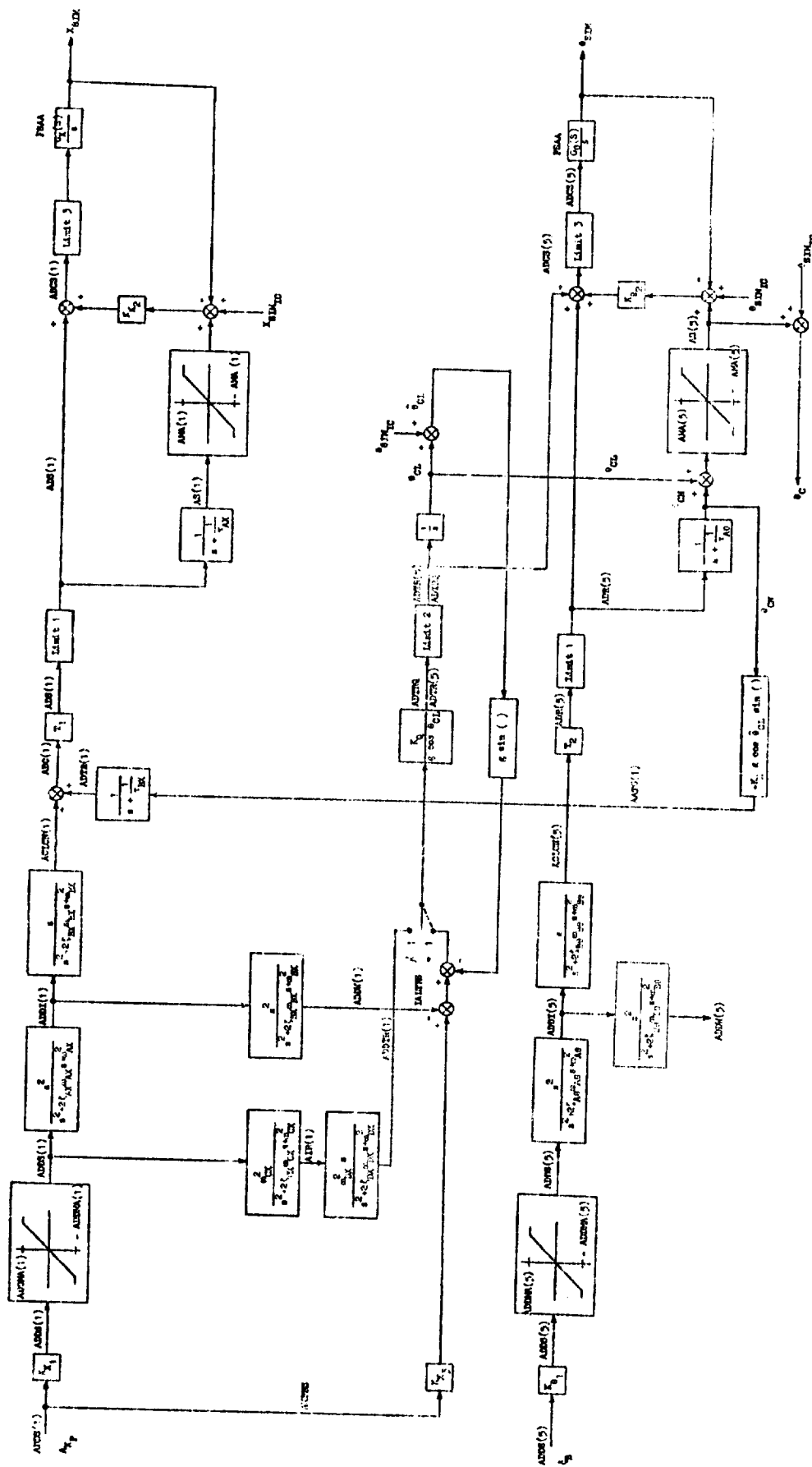
Figure 5.2.2-1: Detailed Block Diagrams of Motion Drive Logic

a. Pitch and Longitudinal
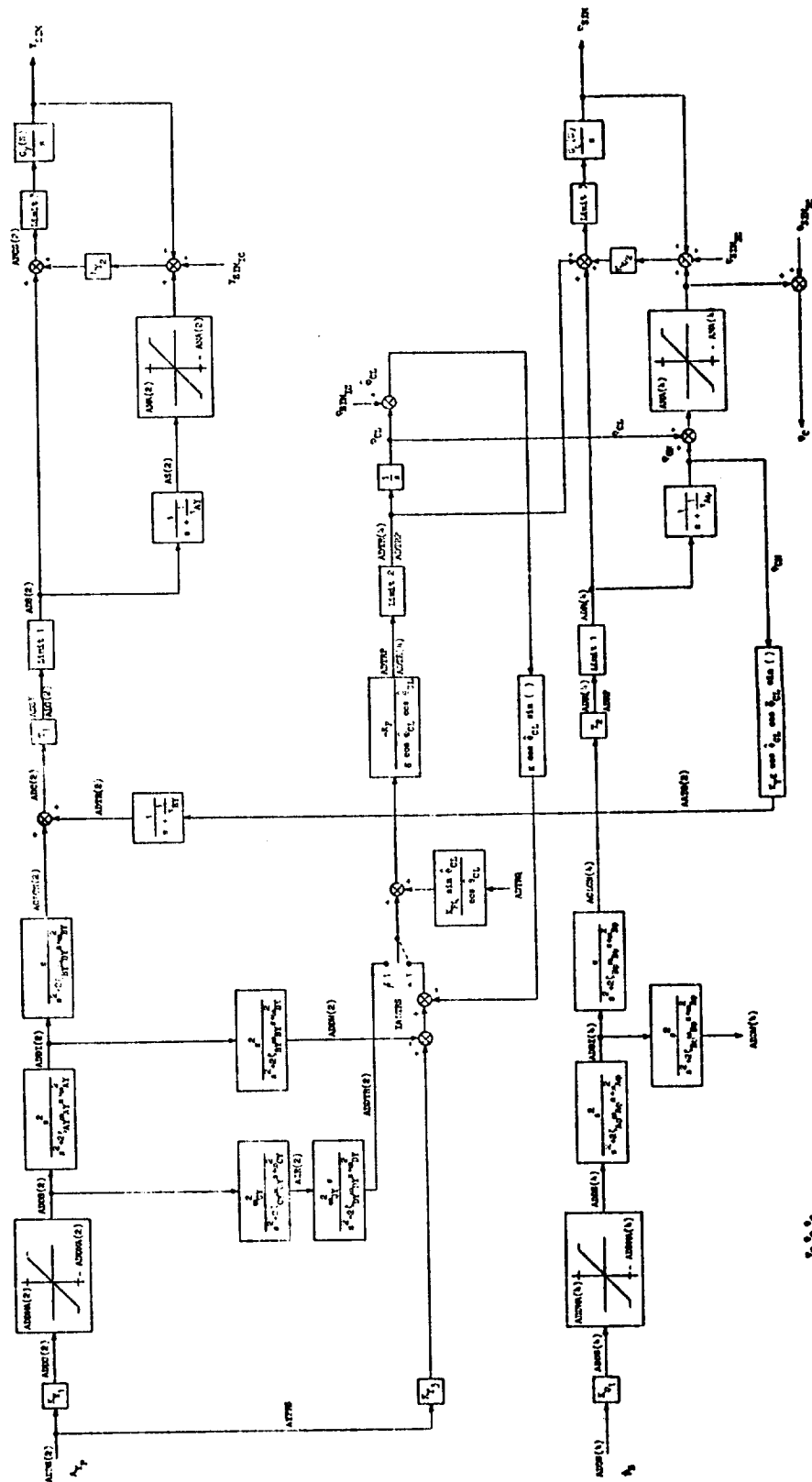
Figure 5.2.2-1 (Continued)

b. Roll and Lateral

Figure 5.2.2-1 (Concluded)

c. Yaw and Vertical
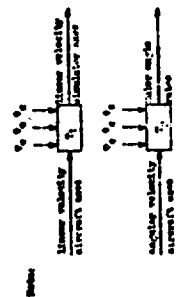
indicated as $G(S)/S$ where the integrator represents the idealized simulator response and all higher order hardware effects are lumped into the $G(S)$. Over the frequency range of concern for the drive logic, each $G(S)$ is very nearly unity.

The various filters indicated in Figure 5.2.2-1 are actually mechanized as difference equations. Note that some of the "integrations" indicated in the general description of the previous subsection are actually first-order lags with large time constants. This is done to avoid open-ended integrations.

Figure 5.2.2-1 indicates the Fortran names for many of the intermediate response variables. Because of many common features among all axes, many of these variables are specified as six-element arrays. The subscript notation generally has the following logic:

Index	Axis
1	X - longitudinal
2	Y - lateral
3	Z - vertical
4	p - roll
5	q - pitch
6	r - yaw

The figure also shows various subscripts on the Euler angles. The meaning of this notation for pitch is as follows:

Symbol	Definition
θ_{CL}	Increment due to residual tilt
$\hat{\theta}_{CL}$	θ_{CL} plus initial condition (or bias) value
θ_{CN}	Component due only to body pitch rate
θ_C	Total simulator pitch angle command including initial condition (or bias) value; used in axis transformations T_1 and T_2

The subscript notation for roll and yaw is identical.

The block diagrams of Figure 5.2.2-1 show several different types of limiters. These are initial acceleration limiters to keep the accelerations within $\pm$ ADDMA(I). On the opposite end are simple position limits, $\pm$ AMA(I), on the pseudo-integrations of the velocity commands. Also included are 3 more complex types, labeled LIMIT 1, 2, 3 in the figure. The logic for these is detailed in Figure 5.2.2-2. The intent of all these limiters is to keep the motion system within the hardware limitations.

The subroutine has several logic options, most of which are not indicated in Figure 5.2.2-1. The one shown there is the choice of residual tilt filter form which is controlled by the integer IALTRS. The option for IALTRS=1 is the one normally used and is the only one which will be discussed subsequently.

There are two options with regard to the pair of second-order filters in each axis. The computer sets $\zeta_{BX} = \zeta_{AX}$, $\omega_{BX} = \omega_{AX}$, $\zeta_{BY} = \zeta_{AY}$, $\omega_{BY} = \omega_{AY}$, etc., unless ISEP=1. The other option is to completely eliminate the A filters. In the block diagrams this is equivalent to setting ω_{AX}, ω_{AY}, ω_{AZ}, $\omega_{A\varphi}$, $\omega_{A\theta}$, or $\omega_{A\psi}$ to zero. This cannot be done physically because the computer algorithm cannot handle zero frequency. The effect is achieved by setting I2ND(I)=1 for I=1,6. This causes the computer to bypass those particular A filters.

The last option provides a simulation of the effects of fuselage bending modes on the vertical and lateral accelerations of the cockpit. This is done by passing the A_{Y_P} and A_{Z_P} inputs through second-order filters with low damping. This filtering is done prior to all the logic shown in Figure 5.2.2-1. Setting IBMDE(1) $\neq$ 0, activates the Y filter and setting IBMDE(2) $\neq$ 0, activates the Z filter.

The Fortran symbols for the various parameters are shown in the block diagram and in Appendix C with their default values. The default values are set by data statements in the subroutine but can be changed. This information is given in Table C-1.

$$\text{ALFZ(I)} = \text{AMA(I)} + \text{ADMA(I)}/\text{C}\phi\text{NSTK(I)}$$

$$|\text{AFU(I)}| \leq \text{ALFZ(I)}$$

N

$$\text{AFU(I)} \cdot \text{ADS(I)} < 0$$

Y   N

$$\text{ADS(I)} = \text{SIGN (ADMA(I), ACLCN(I))}$$

$$\text{ADL(I)} = \text{C}\phi\text{NSTK(I)} \cdot (\text{AFU(I)} - \text{SIGN (AMA(I), ACLCN(I)))}$$

$$|\text{ADS(I)}| > |\text{ADL(I)}|$$

Y   N

$$\text{ADS(I)} = \text{ADL(I)}$$
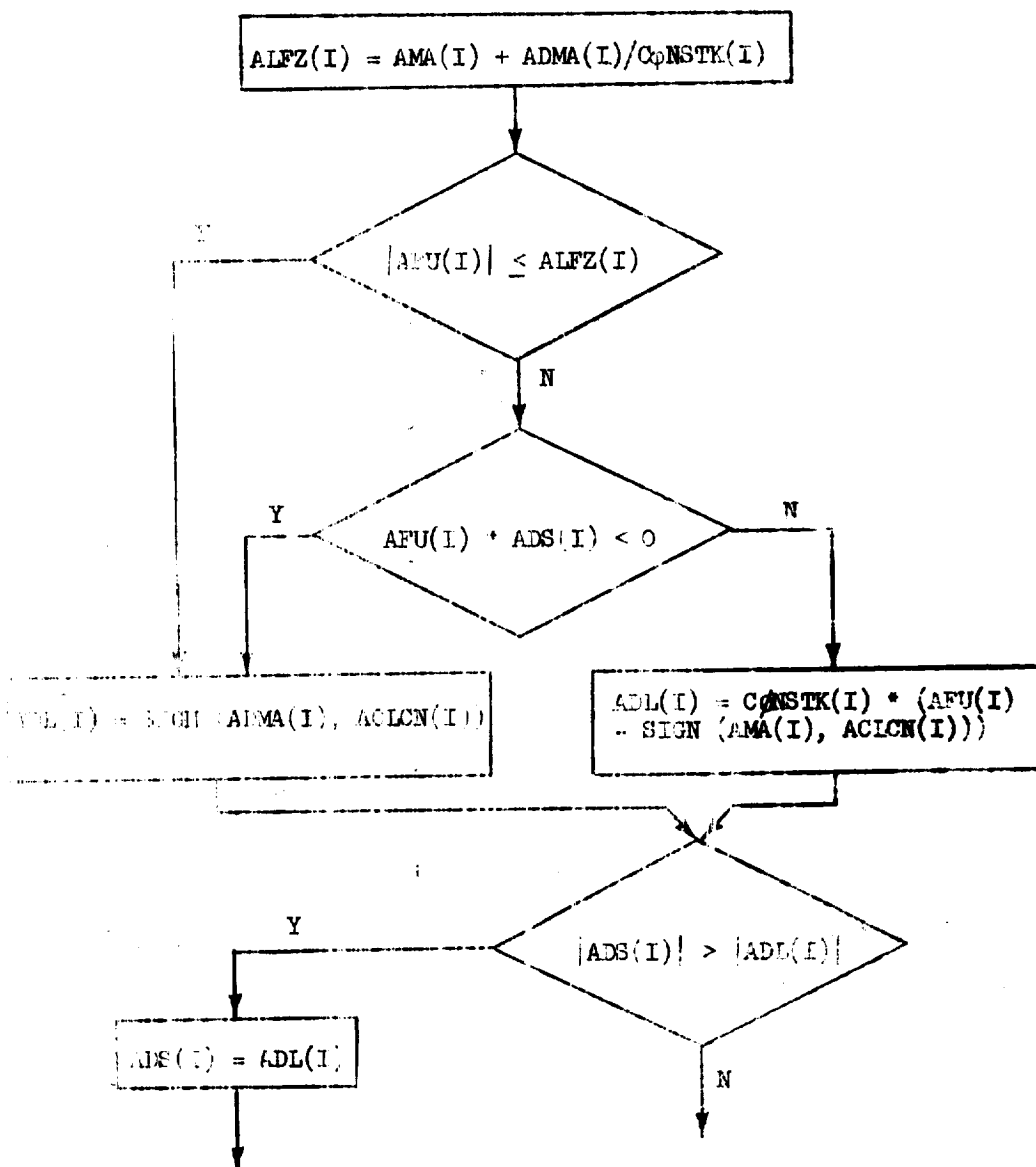
Notes: For angular axes, use ADR instead of ADS in the bottom two boxes

AMA(I)   = Position limit
ADMA(I)   = Velocity limit
AFU(I)   = Simulator position from follow-up pot
CϕNSTK(I) = Array of constants nominally set to:

Longitudinal	Lateral	Vertical	Roll	Pitch	Yaw
-1.804	-0.6	-1.77	-2.0	-2.8	-2.8

Figure 5.2.2-2: Limiter Logic

a. Limit 1

V-36
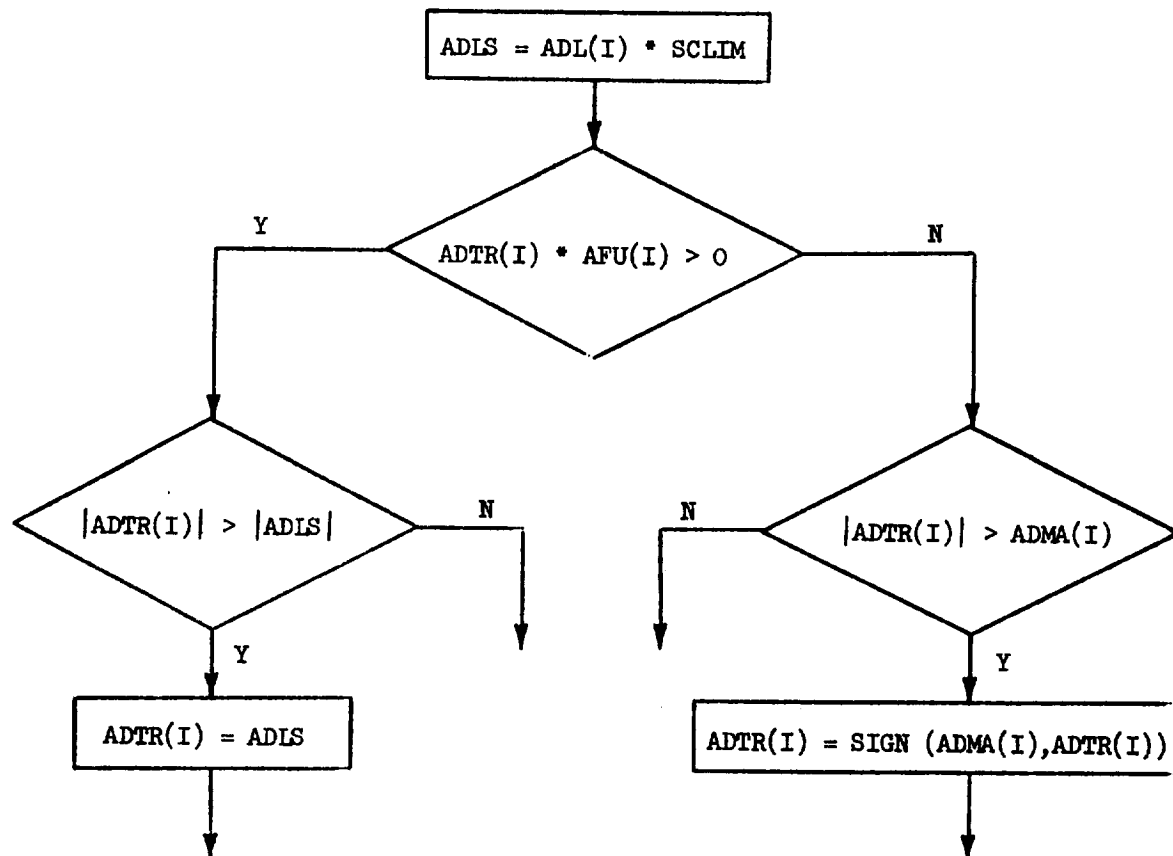
Notes: ADL(I) is the same as in Figure a

SCLIM = Constant, nominal value 0.5

AFU(I) = Simulator position from follow-up pot

ADMA(I) = Velocity limit

Figure 5.2.2-2 (Continued)

b. Limit 2
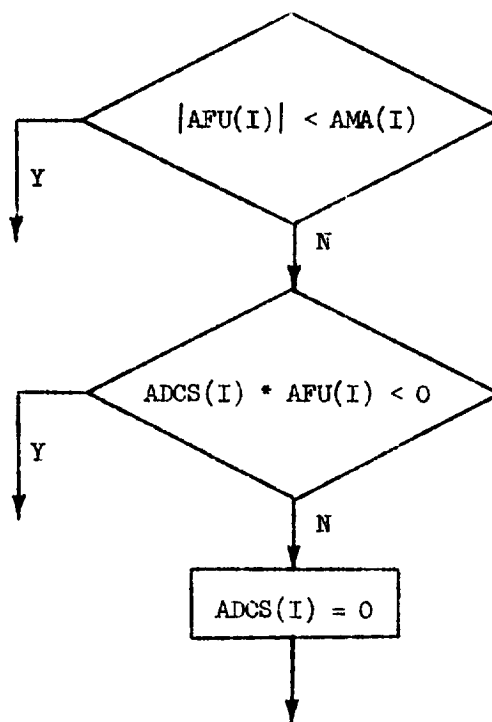
Notes: AMA(I) = Position limit

AFU(I) = Simulator position from follow-up
pot

Figure 5.2.2-2 (Concluded)

c. Limit 3

5.2.3 TRANSFER FUNCTIONS

The complete drive logic presented in the previous subsection is so complex that it is difficult to fully appreciate the effects of various parameters. A primary concern of the researcher is how these parameters can be adjusted to provide the best possible motion fidelity within the physical constraints of the FSAA. These effects can be analyzed by using the transfer functions given in Appendix D. While these transfer functions are mathematically valid only for very small perturbations, they are reasonably accurate right up to the physical response limits of the FSAA.

The transfer functions of Appendix D include the effects of the position drift feedbacks. These effects are lumped within the last pair of parentheses for each transfer function. The dynamic contribution of this term is generally negligible except at very low frequencies.

In Appendix D, the transfer functions for the "recovered" motion, i.e., that which will be experienced by the simulator pilot, are shown. These include the specific forces which can be obtained from:

$$A_{X_{P_{SIM}}} = s^2 X_{SIM} + g\, \theta_{SIM}$$

$$A_{Y_{P_{SIM}}} = s^2 Y_{SIM} - g\, \phi_{SIM}$$

$$A_{Z_{P_{SIM}}} = s^2 Z_{SIM}$$

The "recovered" motion parameters are simply the specific forces and angular accelerations that would be measured in the simulator cockpit. Note that the $g\, \phi_{SIM}$ and $g\, \theta_{SIM}$ terms provide the low-frequency portion of the specific force response thus providing a nearly flat specific force frequency response for the longitudinal and lateral axes. Note also that it is never possible to achieve a flat vertical specific force frequency response as long as the vertical travel is limited. The transfer functions for $A_{X_{P_{SIM}}}$ and $A_{Y_{P_{SIM}}}$ are generally too complex to be given here. However, the next subsection will present some useful approximations.

The functions $G_n(S)$ where $n = \phi, \theta, \psi, X, Y, Z$ represent the hardware dynamics. They generally have little effect at frequencies of interest

in the drive logic design. Data for a second-order model fit to frequency response data for each axis of the motion system were listed earlier in Table 5.1.4-2. These may be taken as the functions $G_n(S)$ for amplitudes where threshold or limiting phenomenon are not encountered.

5.2.4 PHILOSOPHY AND USE OF MOTION SIMULATION

There has been a great deal of physiological research into how a human being senses and perceives motion. There has also been a substantial amount of research into how a human pilot utilizes motion cues and how they affect his performance. However, completely general answers to the following questions are still not available.

- When are motion cues essential for adequate duplication of flight performance or subjective pilot evaluation?

- How much simulator travel is required to adequately simulate a given aircraft and task?

- Given specific simulator capabilities, how should the drive logic be set to most effectively use these motion capabilities?

Consequently, motion simulation is at best an "organized art".

It is beyond the scope of this document to present a complete discussion of the current state-of-the-art in motion simulation. However, the remainder of this subsection briefly discusses two facets of the problem which are of primary concern to the researcher. These are the primary roles of motion cues and human motion perception.

1. Primary Roles of Motion Cues

Having motion cues in a flight simulator can serve several functions. The most important of these are:

- Enhance realism or face validity
- Provide a rapid indication of a discrete disturbance
- Provide useful feedback cues for the pilot.

If the motion cues have any reasonable fidelity, they will obviously increase the simulation realism. The motion will make the pilot feel more like he's flying an airplane even if they fulfill no other purpose. This could make the pilot behave more nearly like he would in an airplane. For example, without motion cues the pilot might use unrealistically large and rapid control inputs.

In some situations motion cues are important to the pilot for detecting a discrete disturbance, such as an engine failure, a control system hardover, a sharp-edged gust, or a wake vortex encounter. In these cases, motion cues allow the pilot to more quickly detect the disturbance. There may be an appreciable lag between a perceptible motion cue and a perceptible visual cue on the instruments or out the window. Furthermore, a visual cue might be missed if the pilot is not looking at the right instrument.

If the above is an important feature of a particular simulation, the basic motion requirement is fairly simple. The motion simulation must only be good enough to provide a clear indication of the disturbance magnitude and sign. This implies duplication of the initial motion cues but they need not be sustained for long periods.

The problem of simulating motion cues which provide useful feedback is the most difficult one for several reasons.

- The importance of a specific motion cue depends heavily on the task and vehicle dynamics.

- In many cases the importance of a specific motion cue has never been thoroughly demonstrated.

- General criteria for adequate motion cue fidelity have not been established.

- Reasonable criteria for linear acceleration fidelity usually result in impractical, or at least very expensive, requirements on linear travel.

The following paragraphs will expand on these points.

In general a pilot will use any feedback, including motion, which aids him in his task. A particular motion cue might be useful because there is no visual equivalent, e.g., detection of sideslip when looking out the window. Some motion cues provide lead information relative to the visual displays. For example, angular motion rates lead the visually perceived attitudes. This information is especially valuable if the pilot must generate lead to stabilize his attitude. As a general rule, the more difficult the task, the greater difference between fixed- and moving-base performance.

The importance of angular motion cues is better understood than the importance of linear cues. There are many examples in the literature on the effects of angular motion on an attitude stabilization task. There are practically none on the effects of linear motion. For example, the importance of vertical motion on a flare and landing task and lateral motion on turn coordination for a conventional aircraft has not been established.

While there are no firm criteria for motion cue fidelity, there are some guidelines. If a motion cue is used in a feedback loop, it is only logical to limit the phase distortion near the crossover frequency for that loop. Based on the limited amount of past data, a reasonable upper limit is 30 deg. For attitude control, crossover frequencies are typically around 3 rad/sec for maximum pilot effort. For path control, crossover frequencies are roughly 0.2 to 0.4 rad/sec for maximum pilot effort.

The above also shows some of the problems in providing enough travel to reproduce linear acceleration cues. For example, if we assume that pilots use vertical acceleration as a cue during flare and landing, the above suggests a vertical washout filter with a frequency on the order of 0.1 rad/ sec or less. This is so low that it would have little effect during the flare maneuver and the simulator vertical motion would have to duplicate that of the airplane. The resulting travel is probably on the order of 15.2 to 30.5 m (50 to 100 feet).

2. Human Motion Perception

The mechanisms by which a human perceives motion include the vestibular system and surface and joint receptors. Past research indicates

that of these the vestibular system is an important source and much physio-
logical research has been devoted to establishing the dynamic properties
of the vestibular system. The intent here is not to minimize the contri-
bution of the surface and joint receptors but to stress the interpretation
of available data.

In the vestibular systems, the semicircular canals provide our sen-
sations of angular rotation. The model shown below is taken from L. R. Young[*].

Roll
velocity
of the
head

$$\frac{9.8\ s}{(s+0.0625)(s+10)}$$

Canal dynamics

$e^{-.3s}$

central
nervous
system
delay

$$\frac{s}{s+0.033}$$
30 sec

Adaptation

2 deg/sec
threshold

Subjective
roll
velocity
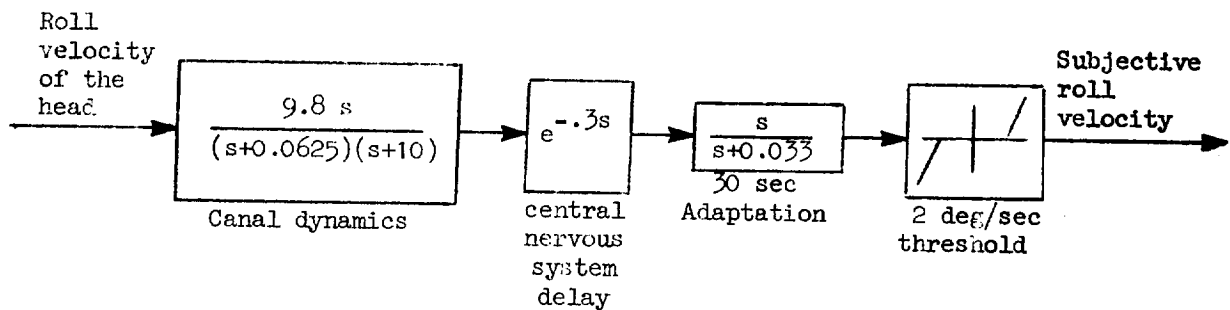
This model shows the semicircular canals as angular __rate__ sensors with the
following key elements: a very low frequency washout, a first-order lag
at 10 rad/sec, and a threshold of roughly 2 deg/sec. These dynamics have
several implications with regard to motion simulation.

● A motion system washout at a frequency as low a. that of
the semicircular canals would have little practical value
(too slow).

● In the frequency range of normal pilot control of attitude,
the perception of angular velocity is quite good.

● It will be difficult to keep spurious angular motions (due
to washouts and residual tilt) below the rate threshold.

The sensation of linear acceleration or tilt relative to the gravity
vector is provided by the otoliths. Young's otolith model[*] is shown below.
The key elements of the model and the simplifications on motion simulation
are summarized below:

*   Young, L. R., "The Current Status of Vestibular System Models", Automatica,
    Vol. 5, pp 369-383, Pergamon Press, 1969.

Lateral specific force → [$\dfrac{1.5}{(s+0.19)(s+1.5)}$] → [threshold block] → [$s + 0.076$] → Subjective lateral acceleration or tilt

Otolith dynamics   0.005 g threshold   neural lead
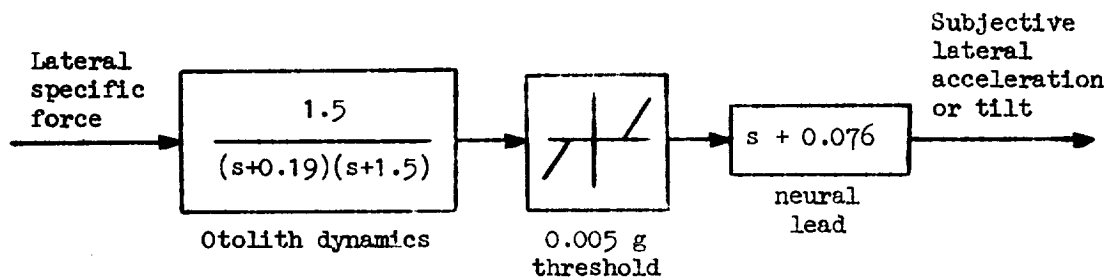
- The threshold is so small, it can be ignored for all practical purposes.

- The lag at 1.5 rad/sec indicates that duplication of specific force cues at frequencies beyond roughly 1 Hz may have little value.

- The lag at 1.5 rad/sec can significantly affect the utility of the cue for tasks such as damping the dutch roll mode using lateral acceleration feedback.

- The steady state gain is finite and 0.4 times the mid-frequency (0.5 - 1 rad/sec) gain; therefore, steady state duplication of specific force is desirable (e.g., by using residual tilt).

Acceptance of the fundamental premise that humans are sensitive to acceleration is the primary rationale for the use of motion systems in flight simulation. The literature, as briefly summarized above, describes many details of human motion sensing processes and, although far from complete and conclusive, this body of knowledge, nevertheless, points to the inclusion of motion as an aid to human orientation perception.

As such, its exact application to each simulation remains open to question and the researcher will ultimately be faced with the decision to use a simulation with motion "cues". Some guidelines and aids will be outlined in this and the next sections.

The concerns of the researcher can be summarized by four statements reflecting the goals that his motion simulation be adequate for his problem, i.e.,

1) The drive scheme is designed from a logical basis

2) That maximum recovery of motion "cues" has been achieved for the travels available

3) That the hardware is following the computer commands with adequate performance

4) That preparations have been made for on-line changes in the drive scheme as required, and provisions for trouble-shooting have been included.

The first goal is achieved by assuming that we know the motion sensing process. The literature states that motion sensing is frequency and amplitude dependent with dynamics that can be approximated by combinations of linear transfer functions and non-linear threshold-type functions. By adjusting the filter break frequencies in the drive logic to be compatible with those in the sensory functions, one ensures that motion is given where it can be sensed somewhat analogous to the production of light at visible frequencies in order to be seen. The other consideration is that the motion to be simulated is sensible, i.e., above thresholds. This points out the important fact that for some simulation problems, motion is not needed. It is probably this premise that accounts for the arguments encountered in the literature on the pros and cons of motion simulation.

Before addressing the second goal, a discussion of motion "cues" recovered is necessary. It is fairly obvious that we sense forces on our bodies through the mechanisms of surface and joint receptors and the vestibular system and that these sensations are integrated in higher centers in the nervous system to form reconstructions of the actual motions. The human response to motion has been described. This suggests upper and lower bounds for the setting of angular motion filter break frequencies but also suggests no lower break frequencies for force simulation. Fortunately the simulation of steady acceleration (or force) in the horizontal plane is facilitated by steady state tilt ("residual tilt") because the human cannot tell the difference between a component of gravity acting on his body or a real linear acceleration (force) provided that the rotation to the proper angle is performed slowly enough that the false angular motion is not perceived.

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In the case of vertical accelerations (forces) the situation is unfortunate and the illusion of steady state vertical acceleration cannot be provided without large vertical travels. In this case it is desirable to maintain normal acceleration filter break frequencies as low as possible.

Bray[*] reports the results of normal axis motion experiments employing a simple second-order filter to drive the Height Control Apparatus simulator at Ames Research Center during simulated transport landings. Filter break frequencies of 0.2 rad/sec were found to be acceptable with unity gain and 0.7 damping ratio. A strong influence of longitudinal handling qualities is also reported.

The recovered motion cues, namely angular and linear acceleration in simulator cockpit body axes, should be as close as possible to the corresponding accelerations at the pilot station of the simulated aircraft while, on the other hand, the motion base travels used to achieve this recovery be as low as possible and at least less than the available travels most of the time. Since limits are present, exceeding these limits with the attentive anomalous decelerations is probably acceptable, say, one or two percent of simulation time provided resets do not occur.

The second goal is accomplished by exercising the tradeoff between the recovered accelerations and the travels used. In practice, this is accomplished experimentally by adjusting filter gains such that the motion travels are not exceeded during specific tasks. This step is preceded by a setting of the break frequencies according to the rationale discussed under the first statement.

The third goal is achieved by ensuring that the hardware response be fast enough to follow the computer commands and can be accomplished by measuring the frequency response properties of the motion base at the frequencies of interest, namely from steady state to at least 10 rad/sec.

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[*] Bray, R. S., Vertical Motion Requirements for Landing Simulation, NASA TM X-62,236, 1972.

The fourth goal is achieved through the inclusion of rapid means of adjusting drive scheme coefficients and by the incorporation of a monitor which can be readily examined to assist in the diagnosing of the results of malfunctions or human errors.

The FSAA system achieves the third and fourth goals by virtue of its performance and equipment. The rapid coefficient change capability inherent in the software allows the user to achieve the second goal and the first goal can only be achieved through continued research.

In summary, the philosophy of motion simulation as suggested here takes the following form:

1) Assume the motion sensing properties of the human and make the drive scheme compatible with it so as to establish a design goal.

2) Perform a series of tradeoff tests following aircraft set-up that provides the best recovery for the travels available.

3) Check the hardware response to ensure it does not compromise the drive logic.

4) Make on-line coefficient adjustments and monitor the motion system to ensure that malfunctions and errors are quickly recognized and corrected.

Further details on the implementation of such a philosophy follows in the next section. All the mechanisms for the exercise of such an approach exist in the FSAA.

5.2.5 DESIGN OF DRIVE LOGIC

In the following section, the design of drive logic will be covered by illustration. In order to accomplish this, simplifications in the logic are made so that the effects of key parameters may be shown. The illustration therefore may not resemble the logic normally used. It is stressed

that the purpose of this section is to acquaint the researcher with the techniques employed so that in the event he feels that some parameters need to be changed for his problem, he will have the background needed. It is the policy of the Simulation Sciences Division to control the motion drive and all suggested changes must be approved by the Division.

The system of algebraic and differential equations comprising the drive scheme is essentially a six-input, twelve-output process. The input quantities are the three components each of specific force and angular acceleration of the pilot's station of the simulated aircraft. The output quantities are the corresponding "recovered" parameters in the simulator cockpit and the six components of position for the motion system. If these arrays of functions are arranged in matrix form the results will look like the following:

"RECOVERED MOTION"

	$\dot{p}_{B_{SIM}}$	$\dot{q}_{B_{SIM}}$	$\dot{r}_{B_{SIM}}$	$A_{X_{SIM}}$	$A_{Y_{SIM}}$	$A_{Z_{SIM}}$
$\dot{p}_B$	Lat				Lat	
$\dot{q}_B$		Long		Long		
$\dot{r}_B$			Yaw			
A_{X_P}		Long		Long		
A_{Y_P}	Lat				Lat	
A_{Z_P}						Vert

"TRAVELS USED"

	φ_{SIM}	θ_{SIM}	ψ_{SIM}	X_{SIM}	Y_{SIM}	Z_{SIM}
$\dot{p}_B$	Lat				Lat	
$\dot{q}_B$		Long		Long		
$\dot{r}_B$			Yaw			
A_{Z_P}		Long		Long		
A_{Y_P}	Lat				Lat	
A_{Z_P}						Vert

In describing the functions to be placed in each square, the time domain (time history for a step input) or the frequency domain (Bode plot) form may be used. The goal of the motion simulation is to make the diagonal terms of the top matrix equal to nearly unity while ensuring that the travels used as expressed in the bottom matrix are less than the travels available. As unity is approached, so must the travels approach the aircraft movements. Of course, the recovered off-diagonal terms should be zero but in practice they will not be so because of the use of residual tilt, e.g., $A_{Y_P} \rightarrow \dot{P}_{B_{SIM}}$, non-linear operation of the servo system and the presence of noise. Manipulating the logic in groups will help clarify the existence of off-diagonal functions. For example, the use of residual tilt to simulate steady state longitudinal acceleration will result in the off-diagonal function $A_{X_P} \rightarrow \dot{q}_{B_{SIM}}$. In all cases a rotation will influence a translation, e.g., $q_B \rightarrow X_{SIM}$ in order to produce no observed $A_{X_{P_{SIM}}}$.

As explained previously, the design manipulations should be in the following groups of the above matrices: pitch and longitudinal (the longitudinal plane), roll and lateral (the lateral plane), and yaw and vertical separate. These groups are labeled in the matrices. The remaining functions should be negligibly small since there is no additional coupling in hardware or software.

The complete linearized transfer functions are presented in Appendix D. In this subsection, these transfer functions will be further simplified so that, as stated earlier, the effects of the key drive logic parameters can be more clearly illustrated. A suggested procedure for adjusting these parameters will also be presented.

The first simplification is to neglect all the long time constants used in pseudo-integrations, i.e., to set all $1/\tau_{An}$ and $1/\tau_{Bn}$ to zero. These time constants are normally too large to significantly affect the motion cues or simulator travel.

The second simplification is to neglect the drive system dynamics, i.e., to set all $G_n(S) = 1$. This is a very good approximation over the frequency range which is affected by the drive logic parameters.

The third simplification is to use only second-order washouts. This is actually done by setting I2ND(I)=1 for I=1,6 in Subroutine BBFND. The effect on the transfer functions of Subsection 5.2.3 is the same as setting all ω_{An} to zero. Second-order washouts[*] are adequate for most, if not all, tasks and make it easier to see the effects of washout frequency and damping ratio.

The last simplification is to assume equal high and low frequency gains for the functions $A_{X_{SIM}}/A_{X_P}$ and $A_{Y_{SIM}}/A_{Y_P}$. This is done by setting $K_{X_3} = K_{X_1}$ and $K_{Y_3} = K_{Y_1}$.

The resulting transfer functions are given in Figure 5.2.5-1 (pitch and longitudinal), 5.2.5-2 (roll and lateral), and 5.2.5-3 (yaw and vertical). Included are asymptote sketches of each frequency response or Bode plot. These sketches clearly demonstrate the major effects of the drive logic parameters for all transfer functions except the commanded-to-recovered specific forces in the longitudinal and lateral axis, $A_{X_{SIM}}/A_{X_P}$ and $A_{Y_{SIM}}/A_{Y_P}$.

The complication in analyzing the $A_{X_{SIM}}/A_{X_P}$ and $A_{Y_{SIM}}/A_{Y_P}$ transfer functions is due to the unfactored form of the numerator. In both cases the numerator is a cubic of the form $s^3 + K (s^2 + 2\zeta_B \omega_B s + \omega_B^2)$. The roots of this polynomial for $\omega_B = 1.0$ rad/sec, and three values of ζ_B can be obtained from the root locus of Figure 5.2.5-4 (note that changing the value of ω_B would simply scale the loci indicated). From Figure 5.2.5-4 it is seen that for each value of ζ_B there is a minimum value of K required for the roots to be in the left-hand plane. This is significant because a non-minimum phase zero in the transfer function for A_{SIM}/A_P will cause large phase distortions. The effect of K on the time and frequency response of A_{SIM}/A_P for one combination of ζ_B and ω_B is shown in Figure 5.2.5-5. It should be remembered that the upper limit of K is determined by the false angular cues (i.e., high values of K yield high values of angular rate to reach the required residual tilt).

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[*] The lowest order of filter that bounds the simulator motions should be used as the phase leads are also the lowest.

Figure 5.2.5-1 Simplified Transfer Functions for the Longitudinal Plane
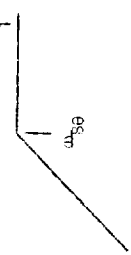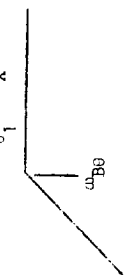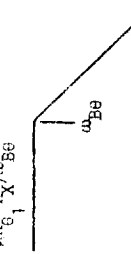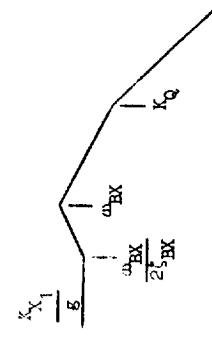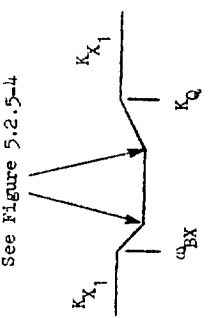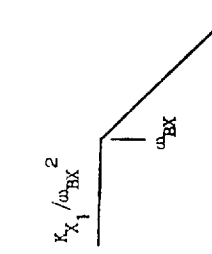
O U T P U T

	θ_{SIM}	$A_{X_{SIM}}$	Y_{SIM}

θ_δ

$$\dfrac{K_{\theta_1} s^2}{s^2 + 2\zeta_{B\theta}\omega_{B\theta} s + \omega_{B\theta}^2}$$

K_{θ_1} ⟍ $\omega_{B\theta}$

$$\dfrac{g K_{\theta_1} s^2 (1 - K_X)}{s^2 + 2\zeta_{B\theta}\omega_{B\theta} s + \omega_{B\theta}^2}$$

$g K_{\theta_1}(1 - K_X)$ ⟍ $\omega_{B\theta}$

$$\dfrac{-g^2 K_{\theta_1} K_X}{s^2 + 2\zeta_{B\theta}\omega_{B\theta} s + \omega_{B\theta}^2}$$

$-g K_{\theta_1} K_X / \omega_{B\theta}^2$ ⟋ $\omega_{B\theta}$

A_{X_D}

$$\dfrac{K_{X_1} K_Q \left(2\zeta_{BX}\omega_{BX} s + \omega_{BX}^2\right)}{g\left(s^2 + 2\zeta_{BX}\omega_{BX} s + \omega_{BX}^2\right)(s + K_Q)}$$

$\dfrac{K_{X_1}}{g}$ $\dfrac{\omega_{BX}}{2\zeta_{BX}}$ ω_{BX} K_Q

$$K_{X_1}\left[\dfrac{s^3 + K_Q\left(s^2 + 2\zeta_{BX}\omega_{BX} s + \omega_{BX}^2\right)}{\left(s^2 + 2\zeta_{BX}\omega_{BX} s + \omega_{BX}^2\right)(s + K_Q)}\right]$$

See Figure 5.2.5-4

K_{X_1} ω_{BX} K_Q K_{X_1}

$$\dfrac{K_{X_1}}{s^2 + 2\zeta_{BX}\omega_{BX} s + \omega_{BX}^2}$$

K_{X_1} / ω_{BX}^2 ⟍ ω_{BX}

Figure 5.2.5-2 Simplified Transfer Function Array for the Lateral Plane
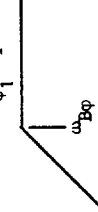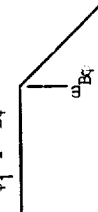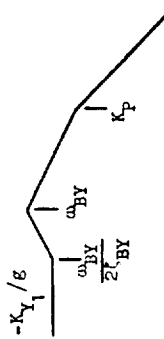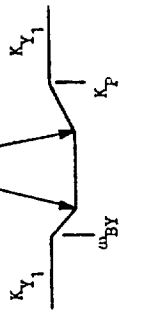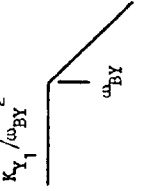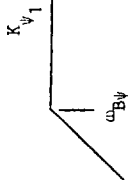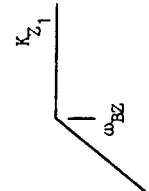
OUTPUT

INPUT	φ_{SIM}	$A_{Y_{SIM}}$	Y_{SIM}
φ_B	$\dfrac{K_{\varphi_1} s^2}{s^2 + 2\zeta_{B\varphi}\omega_{B\varphi} s + \omega_{B\varphi}^2}$	$\dfrac{g K_{\varphi_1} s^2 (K_Y - 1)}{s^2 + 2\zeta_{B\varphi}\omega_{B\varphi} s + \omega_{B\varphi}^2}$	$\dfrac{g K_{\varphi_1} K_Y}{s^2 + 2\zeta_{B\varphi}\omega_{B\varphi} s + \omega_{B\varphi}^2}$
A_{Y_P}	$\dfrac{-K_{Y_1} K_P \left(2\zeta_{BY}\omega_{BY} s + \omega_{BY}^2\right)}{g\left(s^2 + 2\zeta_{BY}\omega_{BY} s + \omega_{BY}^2\right)(s + K_P)}$	$\dfrac{K_{Y_1}\left[s^3 + K_P\left(s^2 + 2\zeta_{BY}\omega_{BY} s + \omega_{BY}^2\right)\right]}{\left(s^2 + 2\zeta_{BY}\omega_{BY} s + \omega_{BY}^2\right)(s + K_P)}$ See Figure 5.2.5-4	$\dfrac{K_{Y_1}}{s^2 + 2\zeta_{BY}\omega_{BY} s + \omega_{BY}^2}$

Figure 5.2.5-3   Simplified Transfer Functions for the Normal and Yaw Axes

INPUT \ OUTPUT	r_{SIM}	$A_{Z_{SIM}}$
r_B	$\dfrac{K_{\psi_1} s^2}{s^2 + 2\zeta_{B\psi}\omega_{B\psi} s + \omega_{B\psi}^2}$ $\quad$ (Bode plot: K_{ψ_1}, $\omega_{B\psi}$)	-----
A_{Z_P}	-----	$\dfrac{K_{Z_1} s^2}{s^2 + 2\zeta_{BZ}\omega_{BZ} s + \omega_{BZ}^2}$ $\quad$ (Bode plot: K_{Z_1}, ω_{BZ})

Figure V.3.5-1. Root Locus of the Polynomial $s^3 + K(s^2 + 2\zeta_B\omega_B s + \omega_B^2)$ for $\omega_B = 1.0$ rad/sec and Three Values of ζ_B

c) Frequency Response

$|G|_{dB}$

ω(rad/sec)

K=2.0
1.0
0.5

K=2.0
1.0
0.5

$\measuredangle G$
(deg)
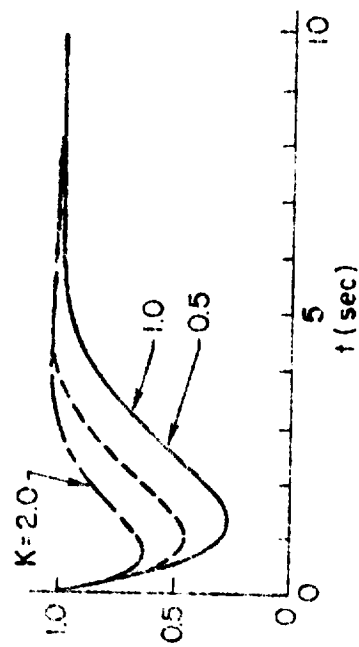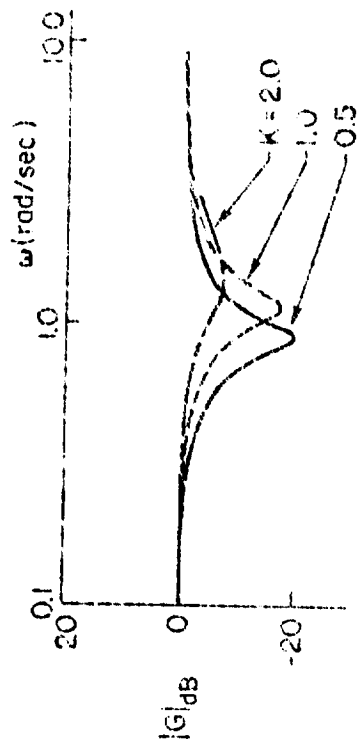
b) Time Response to a Unity Step in Ap

K=2.0
1.0
0.5

t(sec)
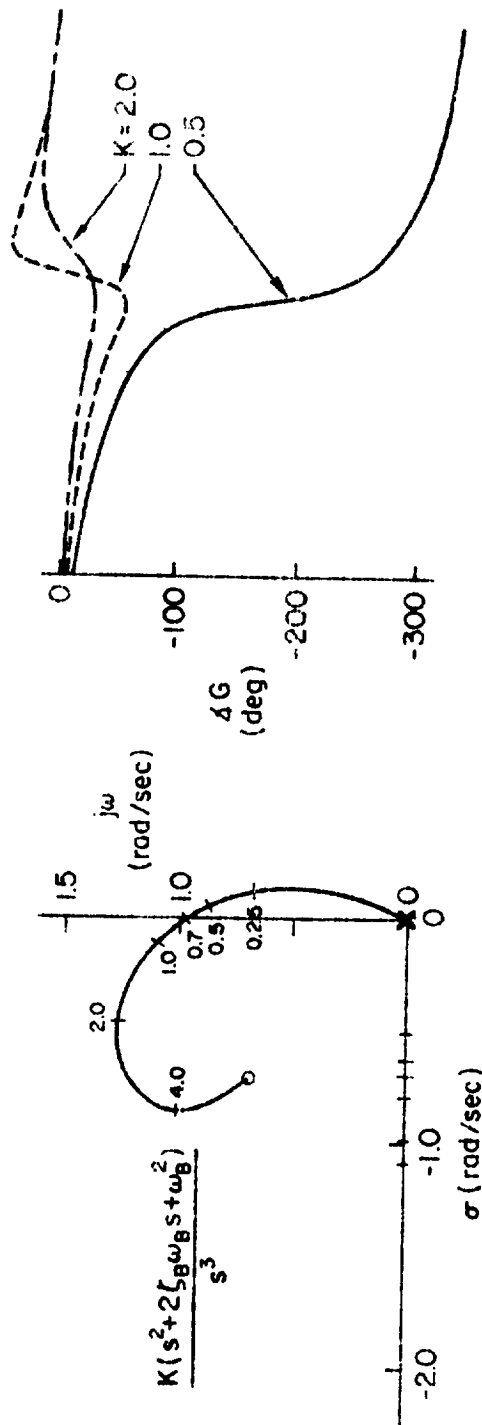
a) Root Locus of Numerator

$\dfrac{K(s^2+2\zeta_B\omega_B s+\omega_B^2)}{s^3}$

$j\omega$
(rad/sec)

σ (rad/sec)

Figure ?.?.?-?. System Survey of the Commanded-to-Recovered Specific Force Transfer Function for $\zeta_B = 0.707$ and $\omega_B = ?.0$ rad/sec

$$G = \frac{A_{sim}}{A_p} = \frac{s^3 + K(s^2 + 2\zeta_B\omega_B s - \omega_B^2)}{(s + K)(s^2 + 2\zeta_B\omega_B s + \omega_B^2)}$$

The transfer functions summaries of Figures 5.2.5-1, 5.2.5-2, 5.2.5-3, and the brief analyses of the specific force transfer functions contained in Figure 5.2.5-4 and 5.2.5-5 show how the various parameters affect both simulator travel and motion cue fidelity. This information should be helpful to the researcher if he wishes to specify the values for his project. The task is still not easy as there are several key parameters to be set and they involve compromises among different motion aspects.

Changing any drive logic coefficient from its nominal value requires the approval of the Simulation Sciences Division.

As stated earlier, this is an "organized" art. There is no clearly established procedure for adjusting the parameters. The approach depends on the simulated task, the aircraft characteristics, and personal preferences. To provide some guidance, the following paragraphs present one such procedure. This procedure is intended for use with a conventional aircraft and simulated tasks which exclude acrobatic maneuvers.

LATERAL PLANE (ROLL AND LATERAL)

1. Set $K_Y = K_{Y_1} = 1$ $(K_{Y_3} = K_{Y_1})$

2. Adjust $\omega_{B\varphi}$, $\zeta_{B\varphi}$, and K_{φ_1} as a compromise between

   - Minimum distortion of the roll response $(\varphi_{SIM}/\varphi_B)$
   and
   - Maximum Y_{SIM} and φ_{SIM} travels used for the expected roll maneuvers and roll disturbances

3. Adjust ω_{BY} and ζ_{BY} to avoid the Y_{SIM} limits for expected maneuvers and disturbances involving maximum A_{Y_P} (e.g., engine failures or decrab)

4. Adjust K_P for acceptable distortion of the lateral acceleration response, $A_{Y_{SIM}}/A_{Y_P}$. (Refer to Figure 5.2.5-4 for the effects of K_P on the numerator zeros.)

5. Determine if the resulting residual tilt rate, P_{SIM}/A_{Yp}, is objectionable to the pilot. If objectionable, reduce K_{Y_1} and start again at step 3 with $K_{Y_3} = K_{Y_1}$.

LONGITUDINAL PLANE (PITCH AND LONGITUDINAL)

1. Set $K_{X_1} = 1$ $(K_{X_3} = K_{X_1})$ and $K_X = 1$

2. Adjust $\omega_{B\varphi}$, $\zeta_{B\varphi}$, and K_{θ_1} as a compromise between

   ● Distortion of the pitch response (θ_{SIM}/θ_B)

   and

   ● θ_{SIM} travel used for the expected pitch maneuvers and disturbances

3. If necessary, reduce K_X to avoid the X_{SIM} limits for expected pitch maneuvers and disturbances.

4. Adjust ω_{BX} and ζ_{BX} to avoid the X_{SIM} limits for maneuvers and disturbances involving A_{X_P} (e.g., throttle chop or braking/acceleration).

5. Adjust K_Q for acceptable distortion of the longitudinal acceleration response, $A_{X_{SIM}}/A_{X_P}$. (Refer to Figure 5.2.5-4 for the effects of K_Q on the numerator zeros.)

6. Determine if resulting residual tilt rate, Q_{SIM}/A_{X_P} is objectionable to the pilot. If objectionable, reduce K_X, and start again at step 4.

YAW AND VERTICAL

Adjust K_{ψ_1}, $\omega_{B\psi}$, and $\zeta_{B\psi}$ $(K_{Z_1}, \omega_{BZ},$ and $\zeta_{BZ})$ as a compromise between

● Distortion of the response ψ_{SIM}/ψ_B (or $A_{Z_{SIM}}/A_{Z_P}$)

and

● Simulator travel ψ_{SIM} (or Z_{SIM}) used for the expected maneuvers and disturbances.

Generally the yaw axis will present a simple design problem as the travel is relatively large. However, the vertical axis emphasizes the traditional deficiency in motion simulation, that is, the large vertical travels required to represent sustained vertical accelerations. The compromise mentioned above depends on the primary function of the acceleration cue. If it will be used as a feedback, the phase distortion at crossover frequency is critical. This limits the washout frequency, and hence K_{Z_1} must be reduced to meet travel limits. If the only function is the detection of large disturbances, it is probably better to use a larger gain, K_{Z_1}, and a faster washout.

5.3 CHECKOUT PROCEDURES

Three kinds of motion system checks are outlined in this section, whose purpose is to aid in establishing fidelity assurance. They are classed into groups forming only hardware checks, initial software checks, and on-line kinds of checks suitable for trouble-shooting.

5.3.1 ON-LINE MONITORING

An on-line monitor is available that places 36 variables on three eight-channel Brush recorders. This is accomplished by multiplexing twelve of the channels into two parts. These 36 variables describe the status of both software and hardware. A list of the monitor variables is given in Table 5.3.1-1.

The array of variables taken from the motion drive logic and the hardware will enable the monitoring of the motion system performance both from the standpoint of the "recovery" motion and the motion travels used. The use of the monitor is explained more fully later.

It is important to understand that these data may sometimes not appear consistent because of different reference frames. For example, the body axis rotational rates p_B, q_B, and r_B are not in the same reference

TABLE 5.3.1-1

NOMENCLATURE FOR MOTION MONITOR

RECORDER 5

CHANNEL	NAME	DESCRIPTION	SOURCE
1	A_{Xp}	Longitudinal Specific Force (ft/sec^2)	Computer; airframe equations of motion
2	$\ddot{X}_{SIM}$	Longitudinal Specific Force (ft/sec^2)	Accelerometer in cockpit
3 Long	$\dot{X}_{CMD}$	Command Longitudinal Velocity (ft/sec)	Computer; motion drive logic
Short	$\dot{X}_{SIM}$	Simulator Longitudinal Velocity (ft/sec)	Tachometer on longitudinal axis
4 Long	$\dot{X}_{DR}$	Drive Rack Command Longitudinal Velocity (ft/sec)	Drive rack (Servo input)
Short	X_{SIM}	Longitudinal Position (ft)	Longitudinal axis follow-up potentiometer
5	A_{Yp}	Lateral Specific Force (ft/sec^2)	Computer; airframe equations of motion
6	$\ddot{Y}_{SIM}$	Lateral Specific Force (ft/sec^2)	Accelerometer in cockpit
7 Long	$\dot{Y}_{CMD}$	Command Lateral Velocity (ft/sec)	Computer; motion drive logic
Short	$\dot{Y}_{SIM}$	Simulator Lateral Velocity (ft/sec)	Tachometer on lateral axis
8 Long	$\dot{Y}_{DR}$	Drive Rack Command Lateral Velocity (ft/sec)	Drive rack (Servo input)
Short	Y_{SIM}	Lateral Position (ft)	Lateral axis follow-up potentiometer

Note: "Long" indicates the multiplexed channel component that shows the variable with a time duration of approximately 0.9 sec. The "short" channel time is about 0.1 sec.

"long" variable

zero

"short" variable
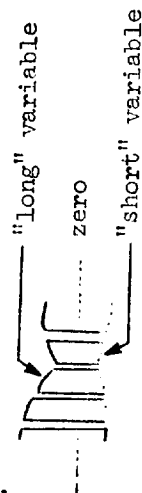
TABLE 5.3.1-1 (Continued)

RECORDER 6

CHANNEL	NAME	DESCRIPTION	SOURCE
1	A_{Z_P}	Vertical Specific Force (ft/sec^2)	Computer; airframe equations of motion
2	$\ddot{z}_{CMD}$	Filtered Vertical Specific Force (ft/sec^2)	Computer; motion drive logic (only used as a monitor, not a simulator drive command)
3	$\ddot{z}_{SIM}$	Vertical Specific Force (ft/sec^2)	Accelerometer in cockpit
4 Long	$\dot{z}_{CMD}$	Command Vertical Velocity (ft/sec)	Computer; motion drive logic
Short	$\dot{z}_{SIM}$	Simulator Vertical Velocity (ft/sec)	Tachometer on vertical axis
5 Long	$\dot{z}_{DR}$	Drive Rack Command Vertical Velocity (ft/sec)	Drive rack (Servo input)
Short	z_{SIM}	Vertical Position (ft)	Vertical axis follow-up potentiometer
6 Long	$\dot{\psi}_{CMD}$	Command Yaw Gimbal Velocity (deg/sec)	Computer; motion drive logic
Short	$\dot{\psi}_{SIM}$	Simulator Yaw Gimbal Velocity (deg/sec)	Tachometer on yaw gimbal axis
7 Long	$\dot{\psi}_{DR}$	Drive Rack Command Yaw Gimbal Velocity (deg/sec)	Drive rack (Servo input)
Short	ψ_{SIM}	Yaw Gimbal Position (deg)	Follow-up position potentiometer on yaw gimbal axis
8	$\dot{p}_B$	Aircraft Body Axes Roll Acceleration (deg/sec^2) OR	Computer; airframe equations of motion
	$\ddot{\psi}_{SIM}$	Simulator Yaw Gimbal Acceleration (deg/sec^2)	Accelerometer on yaw gimbal axes

TABLE 5.3.1-1   (Concluded)

RECORDER 7

CHANNEL	NAME	DESCRIPTION	SOURCE
1	$\dot{p}_B$	Aircraft Body Axes Roll Acceleration (deg/sec^2)	Computer; airframe equations of motion
2	$\ddot{\phi}_{SIM}$	Simulator Roll Gimbal Acceleration (deg/sec^2)	Accelerometer on roll gimbal axis
3 Long	$\dot{\phi}_{CMD}$	Command Roll Gimbal Velocity (deg/sec)	Computer; motion drive logic
Short	$\dot{\phi}_{SIM}$	Simulator Roll Gimbal Velocity (deg/sec)	Tachometer on roll gimbal axis
4 Long	$\dot{\phi}_{DR}$	Drive Rack Command Roll Gimbal Velocity (deg/sec)	Drive rack (Servo input)
Short	ϕ_{SIM}	Roll Gimbal Position (deg)	Follow-up position potentiometer on roll gimbal
5	$\dot{q}_B$	Aircraft Body Axis Pitch Acceleration (deg/sec^2)	Computer; airframe equations of motion
6	$\ddot{\theta}_{SIM}$	Simulator Pitch Gimball Acceleration (deg/sec^2)	Accelerometer on pitch gimbal axis
7 Long	$\dot{\theta}_{CMD}$	Command Pitch Gimbal Velocity (deg/sec)	Computer; motion drive logic
Short	$\dot{\theta}_{SIM}$	Simulator Pitch Gimbal Velocity (deg/sec)	Tachometer on pitch gimbal axis
8 Long	$\dot{\theta}_{DR}$	Drive Rack Command Pitch Fimbal Velocity (deg/sec)	Drive rack (Servo input)
Short	θ_{SIM}	Pitch Gimbal Position (deg)	Follow-up position potentiometer on pitch gimbal axis

system as the Euler angle rates, $\dot{\phi}_{SIM}$, $\dot{\theta}_{SIM}$, and $\dot{\psi}_{SIM}$. On the other hand, the specific forces A_{X_P}, A_{Y_P}, and A_{Z_P} are in the same reference as $\ddot{X}_{SIM}$, $\ddot{Y}_{SIM}$, and $\ddot{Z}_{SIM}$, the cockpit measured accelerations. Actually the terms $\ddot{X}_{SIM}$, $\ddot{Y}_{SIM}$, and $\ddot{Z}_{SIM}$ are misnomers as they are not the second derivatives of cab position X_{SIM}, Y_{SIM}, and Z_{SIM} because X_{SIM}, Y_{SIM}, and Z_{SIM} are referred to earth-fixed axes while $\ddot{X}_{SIM}$, $\ddot{Y}_{SIM}$, and $\ddot{Z}_{SIM}$ are referred to cockpit-fixed axes.

When comparing body axes rotational rates with gimbal axis rates, consider that gimbals are a serial arrangement of axes that are driven to align the cab with the direction specified by the Euler angles in the drive logic. These gimbal angles, therefore, may bear little resemblance to the orientation of the simulated aircraft.

The quantities labeled "DR", meaning drive rack, pertain to the drive rack command signals to each servosystem and as such equal the computer-generated velocity commands only in the operate mode. For the remaining time, it shows the commands to the system for centering, docking, limit braking, and resets. The drive rack and the computer-hardware interface is described more fully in Subsection 5.1.2.

A trunking diagram of the monitor setup is shown in Figure 5.3.1-1. Note that the signal multiplexing is done by an analog computer and that the commands to each actuator are sent directly to the monitor as are the hardware feedbacks. In this way, no time delays are present.

The on-line monitor should be used throughout a simulation period to insure proper operation of the motion system. Examination of the monitor variables should permit detection of any significant hardware malfunctions. The simplest hardware check is to compare the motion base commands and the tachometer feedbacks, e.g., compare $\dot{X}_{CMD}$ (or $\dot{X}_{DR}$) with $\dot{X}_{SIM}$. The on-line monitor also provides a way to roughly check the motion recovery, e.g., by comparing A_{X_P} with $\ddot{X}_{SIM}$ or $\dot{p}_B$ with $\ddot{\phi}_{SIM}$.

Cab

Drive Rack

Σ^9

3C

Recorder
No. 5, 6, 1

COMCOR 175
Analog Computer
"Multiplexer" and
Gain Scheduler

DR — Drive Rack
TAC — Tachometer
FU — Follow-up Potentiometers
ACC — Accelerometers
CMD — Computer Command
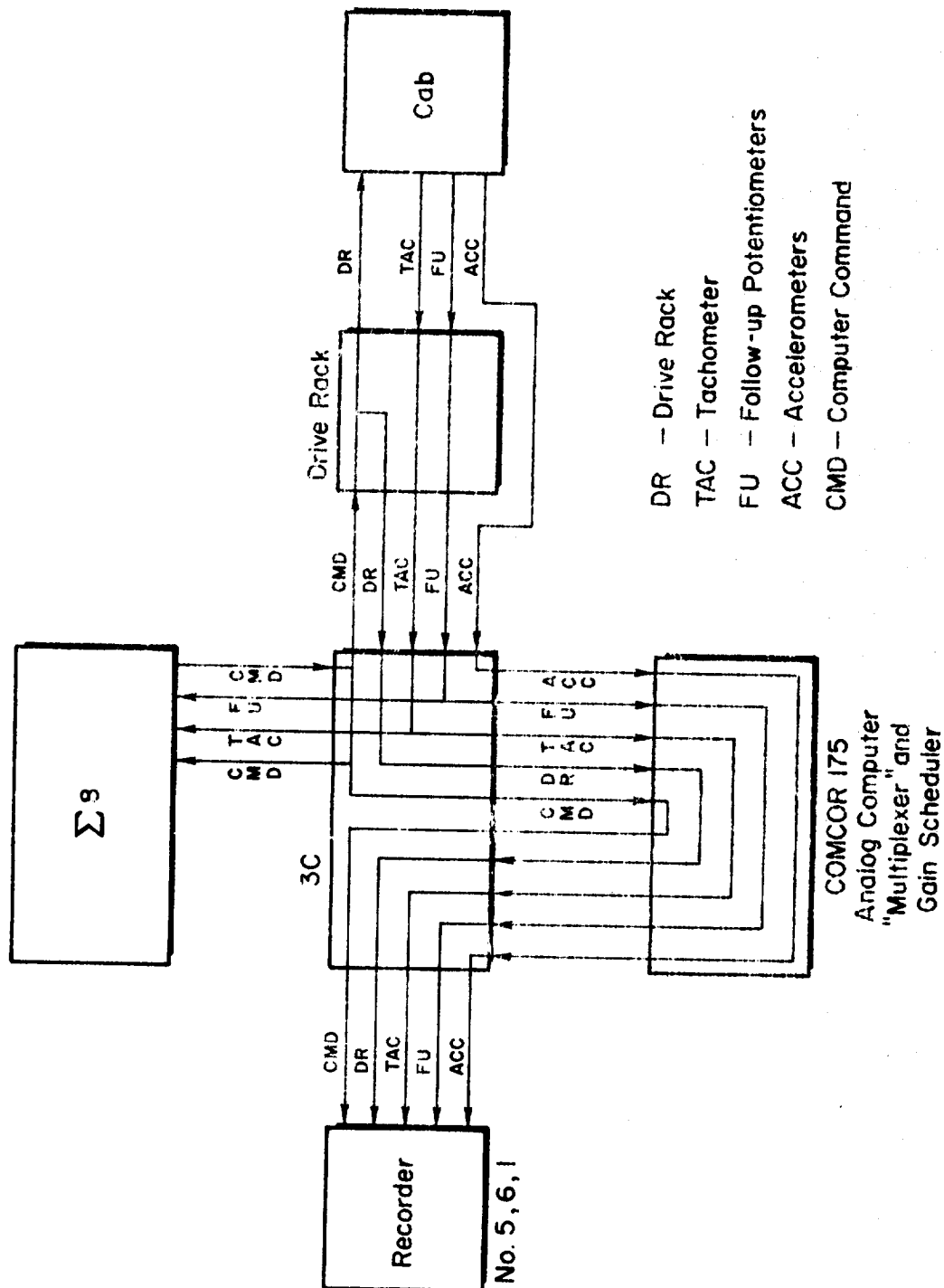
Figure 5.3.1-1: Trunking Diagram of the Motion Monitor

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5.3.2 INITIAL HARDWARE CHECKS

Periodically, the motion system is exercised in such a way that its command-following performance can be assessed. The exercising can consist of response measurements from simple steps of velocity command to the Fourier Analysis of the response to quasi-random inputs.

SAFE (Six-Axis Frequency Evaluation) is a program designed to measure the frequency response of the motion base. The researcher is referred to the Reference[*] where a detailed description of the method is given. Some exerpts from this work are given below.

Up to all six axes of the motion base are simultaneously driven by a sum of sinusoids for each axis. The position follow-up signals are used to calculate the frequency response. The results of this measurement provide a sensitive check of the entire motion system, and readily verify correct operation of the system elements and continuity to and from the hardware. The program measures the response to the sum of eleven sinusoids that generally range in frequency from approximately 0.2 rad/sec to 20 rad/sec[**]. The signs of the sinusoids are alternated so as to avoid large initial transients. A fast Fourier Transform algorithm is used to analyze the signals from the various follow-up pots to reduce computation time. The advantages of this technique are that the bulk of calculations can be performed while the data are being taken; the data do not have to fit in memory for the algorithm to be used; and it is extremely fast, reducing the total computation time after the simulator run to less than five seconds. The run time is about one minute.

Three modes of operation for SAFE are available, all involving different test elements. In the first mode, the sum of sinusoids is analyzed without further processing to provide a check on the SAFE arithmetic operations. In the second mode, an analog integrator is driven by the sum of sinusoids (converted to analog form) and the response is converted back

---

[*] SAFE: Six-Axis Frequency Evaluation of a Motion Simulator, R. S. Shirley and A. D. Jones, AIAA Paper No. 73-932, September 1973.

[**] All frequencies are inversely proportional to computer frame time.

into digital form, differentiated, and analyzed. The phase error introduced by the sampling process can be measured this way.

In the third mode, the sums of sinusoids drive the motion base actuators and their position is sensed by the follow-up pots. These signals are then fed back to the digital computer for differentiation and analysis. A correction is applied for the sampling phase error which was measured using the second mode.

The SAFE program not only computes the Fourier coefficients for each input frequency, but also for twelve frequencies between and outside these. An assessment of noise is made by comparing the magnitude of the coefficients for the in-between and input frequencies. A typical printout of a SAFE run will show the amplitude ratio and phase angle for the frequency response function and the Fourier coefficients for the eleven input frequencies. It also will show the Fourier coefficients for the twelve frequencies that are in-between and outside the input sinusoids. If the noise is excessive at a particular input frequency, the printout shows 10^4 for the amplitude ratio and phase angle.

SAFE has the option of being run with or without the drive logic, e.g., the sum-of-sinusoids input can be applied as A_{X_p} or as a direct velocity command, $\dot{X}_{CMD}$. The latter option measures only the hardware dynamics and the other includes the drive logic dynamics. Running SAFE with the drive logic is not recommended. The drive logic generally has crossfeeds (between pitch and longitudinal and between roll and lateral) which make the transfer function measurements uninterpretable, except for the uncoupled axes.

This problem can be avoided by making two SAFE runs. One run would have $\dot{p}_B$ and $\dot{q}_B$ inputs with A_{X_p} and A_{Y_p} equal to zero. The reverse condition would be used for the other run. The transfer functions under these conditions do have physical meaning. However, the SAFE program was not really designed to check the software and most of the interesting transfer functions (those given in Figure 5.2.5-1, 5.2.5-2, and 5.2.5-3) are not measured. Some other technique must be used to check the software (see the next subsection).

SAFE runs are made weekly to provide a fairly complete check of the hardware performance. Daily checks of the motion base are made with a simpler program. This program merely provides simple commands to each of the axes sequentially. Comparison of the FSAA time responses with a standard set provides a cross check of the hardware.

5.3.3 INITIAL SOFTWARE CHECKS

Unfortunately there is no simple method of checking the software to verify that the drive logic is performing as intended. The only practical approach is to measure the system responses to simple, discrete (e.g., steps) inputs of A_{X_p}, A_{Y_p}, A_{Z_p}, $\dot{p}_B$, $\dot{q}_B$, and $\dot{r}_B$. These responses[*] should be compared with similar responses computed from an off-line supporting analysis using the transfer functions of Appendix D. The comparison should be made for relatively small inputs to avoid significant drive logic non-linearities and limiters. Larger inputs can be used to check the operation of the limiters.

A descriptive and complete system check can be accomplished using the data set described in Subsection 5.3.1 for hardware checks, except that in this case the drive logic coefficients are left at their nominal design values. The introduction of steps of angular and linear acceleration into the drive logic with the hardware following the computer commands should reveal all aspects of system performance through the motion system monitor. A standard check case can be configured during the final unpiloted validation phase, checked against hand calculations or the off-line support program and used daily to ensure that all aspects of the motion system including the computer and monitor are operating properly.

For example, a step of longitudinal specific force will surge the cockpit and pitch it such that the recovered longitudinal acceleration will resemble that from the off-line support program. The residual tilt component should be apparent and by simply increasing the magnitude of the input, limit operation can be observed.

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[*] These tests can be run without the motion base by using the dummy follow-up option in Subroutine BBEND.

5.3.4 TROUBLE SHOOTING

Trouble shooting is that aspect of simulation that deals with diagnosing problems and application of fixes. Sometimes a malfunction can only be corrected by an extensive equipment overhaul. During this activity, tests may be suspended by the facility manager so the decision to completely shut down will be made only after the failure of all possible "quick fixes". In these instances, the researcher is encouraged to assist in the trouble shooting.

Problems arise from two basic causes:

1) Limit operation

2) Equipment malfunction.

Limit Operation

The key to effective trouble shooting of limit operation is the motion system monitor. By first ensuring that the feedback elements supplying it with data are correctly calibrated and operating, it will be the first documentor of a problem. Besides showing a second-by-second record of the velocity following properties of each axis, undue system noise through the accelerometers, continuity difficulties, and improperly set coefficients, the limiting aspect of motion simulation is also readily shown. In most cases, the limits that are usually reached are the software limits. When this happens an anomalous deceleration occurs that will be recorded by the cockpit accelerometers. The command and drive rack velocities should also show this phenomenon. When an axis such as lateral is on a limit, i.e., stopped, the lateral cockpit accelerometer will cease to show signals similar to lateral specific force but rather similar to cockpit roll angle. Some limit operation is to be expected and is not to be considered as "improper" or "incorrect". Reaching the limits is simply the result of a drive logic that is demanding more performance than is available from the hardware. Pilots should not modify their behavior because of reaching limits nor should the aircraft performance be changed because of it. Instead, the drive logic coefficients should be changed if the limits are reached with unacceptable frequency.

One method of reducing demanded motion performance is to reduce the forward gains. Following each input into the drive logic are simple gains and acceleration limits. If the gains are set too high, the maximum response of some of the motion base actuators may exceed their available travels and reach a limit.

Resets sometimes may be troublesome and should be avoided because of the re-engagement time involved. Resets are caused by the automatic monitoring system which seeks to protect the hardware from damage that could be caused by demanding excessive performance. These performance limitations are described in Section 5.1.3. Another battery of limits in the computer software are set so as to command the hardware to avoid demanding excessive performance. As such, they are set lower than the "hardware reset limits" and therefore should prevent resets. As unlikely as they are to occur, the most likely cause might be a change in monitor hardware properties. It is always desirable to set the software limits only a few percent of travel inside the hardware limits. The variability of hardware function especially with changing temperature conditions is not always known so when an incompatibility results, care is exercised not to unnecessarily set the software limits too low. It is such a trend that could eventually result in a wide descrepancy between the two. By periodically exercising the limits, their stopping performance may be compared to the reset limits and the software limits set so that they stop each axis just short of the reset limit.

Equipment Malfunction

The hardware may be classified into three broad groups: the computer, the interface, and the servosystem. To this triad, a monitor is integrated that reveals the output of these components. The digital-to-analog converters (DAC's) carrying drive and status data (e.g., $\dot{X}_{CMD}$ and A_{X_P}) are monitored, giving an indication of the computer state. Next, the drive rack outputs (e.g., $\dot{X}_{DR}$) are displayed showing the processing of the commands due to the mode selected. Last in line are the feedback elements themselves sensing the actual movements of the cockpit. If this sequence is kept in

mind during periods of suspected malfunction, a brief examination of the monitor records may point to the deficient component.

For example, a large difference between $\dot{X}_{CMD}$ and $\dot{X}_{DR}$ during operate condition points to either improper mode control or a malfunctioning drive rack. Another example is a large difference between $\dot{X}_{DR}$ and $\dot{X}_{SIM}$. In this case three malfunctions are possible:

1) The trunking to the servo drive is not carrying the drive command properly

2) The servosystem itself is malfunctioning

3) The feedback tachometer is malfunctioning.

In such a case it may be possible to determine the cause on-line thereby providing the researcher with enough information to decide whether or not to stop. It should be remembered that after stopping, the decision to re-start is made by the facility manager. By cross-checking the tachometer output against the follow-up-pot output, it may be determined that the tachometer itself is deficient and perhaps not necessary to the tasks at hand.

In another example, the accelerometer output $\ddot{X}_{SIM}$ may not resemble A_{Xp}. Again, a quick calibration of the accelerometer may be made by cross-checking its output against the pitch follow-up pot. During periods where the longitudinal actuator is not accelerating, the accelerometer should indicate a component of gravity which can be estimated from the pitch follow-up pot indication. If this test yields positive results, a longitudinal limit may have been reached, indicated by the longitudinal follow-up pot reading X_{SIM}. If not, the longitudinal actuator may be the cause.

The key to identifying equipment malfunction are the monitor records and as such should be kept running when the servo loops are closed. An event marker indicating that a limit has been reached can be implemented. Periodic calibration of the cockpit feedbacks including the daily accelerometer standardization establishes the credibility of the monitor. The pilot can often detect malfunctions and generally his comments can be correlated very

well with the monitor data. A difficulty here is that some of the anomalous
apparent force and angular velocity sensations reported by the pilot may in
fact be part of the normal operating envelope, e.g., the anomalous apparent
longitudinal acceleration felt during pitching maneuvers where the cockpit
pitches but the longitudinal actuator does not accelerate due to restrictions
in its travel.

SECTION 6

SIMULATION PROCEDURES

6.1 PRE-SIMULATION PLANNING

6.1.1 APPLICANT REQUIREMENTS AND PROCEDURES

The FSAA is a government-owned facility created to serve the research needs of the aeronautical and astronautical communities. Any individual or group within the United States who is actively engaged in research and development of aeronautical or astronautical systems (considered to be in the National interest) and can show good reasons for requiring the FSAA may apply. Each application is reviewed by NASA, and if approved, the applicant receives a committment of facility time and resources within a specified time frame. Initial inquiries should be made to the cognizant organizational director:

Director of Aeronautics and Flight Systems
NASA Ames Research Center
Moffett Field, California   94035

Informal inquiries regarding additional facilities information may be directed to the Assistant Chief (Operations) of the Simulation Sciences Division at the above address.

6.1.2 THE NEED FOR PRE-SIMULATION PLANNING

The importance of pre-simulation planning cannot be overstressed. Because of the diverse viewpoints of the various groups involved and the many different kinds of hardware employed, effective planning and communication are essential to a successful simulation. The FSAA system is an unique facility expressly designed to serve the research community.

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Its components were built to provide a wide range of characteristics that were determined to be adequate for research-type investigations. Due to today's high technology environment, the equipment is constantly being upgraded and people's skills in the use of this equipment is always improving. The situation is one of constant change. Any high-technology facility in a state of flux requires good communication and realistic planning in order to achieve reasonable productivity. The purpose of the rest of this section is to provide guidance in the creation of an experimental plan and outline procedures that can be used to implement it. The following paragraphs outline the ingredients of such a plan.

Statements of Test Objectives

To help coalesce the plan, brief statements of test objectives can serve to stimulate thought in the direction of efficiency. They should include the central research questions such as:

"What is the effect on landing performance of various flight control system modifications?"

Within the central research question lies the beginning of the process of:

- Selection of FSAA components
- Configuration of these components.

Some idea of the answer is usually available from the researcher in the form of estimates, judgments, or guesses. Again, clear statements reflecting these possibilities help in formulating the plan.

Schedule of Events

The most important component of the plan is the schedule. Since there are many factors to be coordinated including simulator maintenance, use of simulation hardware by other simulators, as well as all elements of the subject simulation, it is important that the schedule show the beginning

and end of a task and how its result interacts with the others. The important events that should be addressed might include:

- First conference; preliminary briefings

- Researcher preparation of test plan

- Second conference; plan review, establishment of test time period

- Researcher preparation of data required

- Data package and hardware requirements delivered

- Computer programming

- Hardware modification/installation

- Software checkout

- System checkout

- Test plan verification

- Test period

- Test data processing as required.

An example of time sequencing of these events is shown in Figure 6.1.2-1.

6.1.3 INFORMATION EXCHANGE REQUIREMENTS

Although the researcher and the Simulation Sciences Division exchange information, most of the flow is from the researcher. The following is a list of typical data the researcher should include in the data package delivered to the Simulation Sciences Division. Figures 6.1.3-1 to 6.1.3-4 contain forms that aid the preparation of this package.

Weeks Relative to FSAA Occupancy

1. First conference
2. Preparation of test plan
3. Second conference
4. Preparation of data required
5. Delivery of data package
6. Computer programming
7. Hardware modification/installation
8. Software checkout
9. System checkout
10. Test plan verification
11. Test period
12. Data processing

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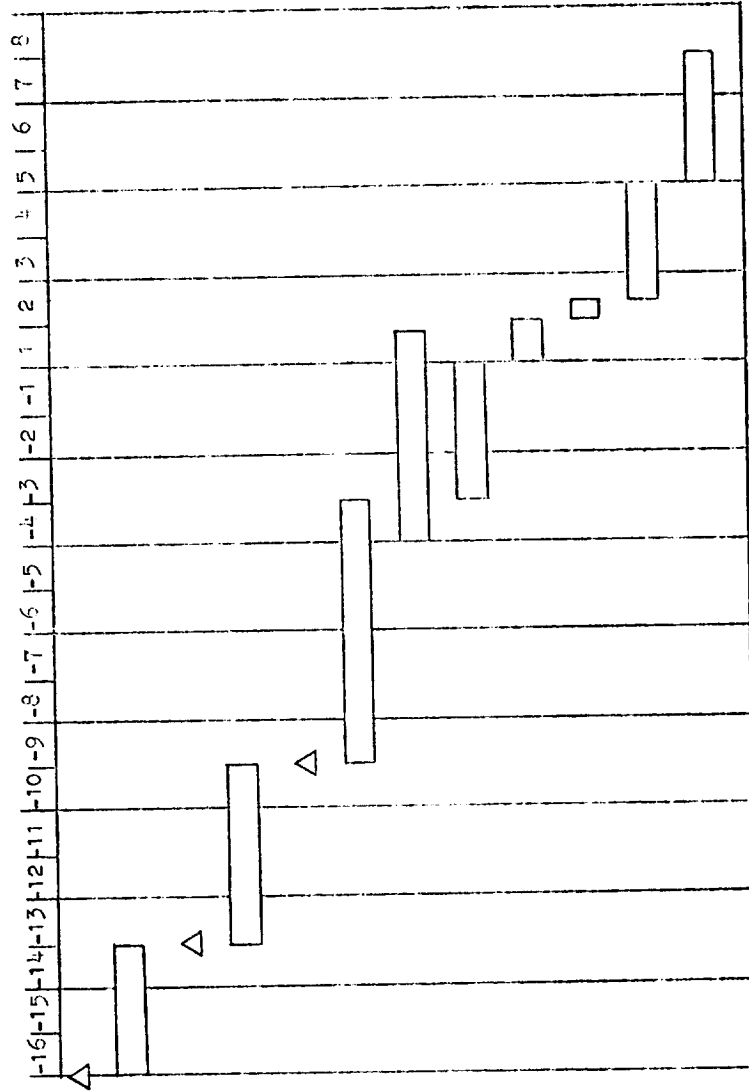
Figure 6.1.2-1: Example Schedule

Figure 6.1.3-1: Control Manipulator Requirements

PROJECT TITLE_____
PROJECT ENGINEER_____ TELEPHONE_____
OPERATIONS MANAGER_____ TELEPHONE_____
SIMULATOR_____ RIGHT/LEFT SEAT_____
SIMULATOR START DATE_____ J.O._____

FLIGHT CONTROL HARDWARE REQUIREMENTS
    Flight Control Hardware Requirements should be in from 4 to 12
    weeks before start date. The above time span depends upon
    avaliable manpower, complexity of design, existing hardware and
    prior development. The Operations Manager should be notified
    at the earliest possible date to insure avaliability of flight
    control hardware for simulator start date.

FLIGHT CONTROL CONFIGURATION

Type Control		Location and Description
Flap		
Collective		
Spoiler		
Throttle	How Many	
After Burner		
Auto. Throttle		
Diverter		
Thrust Vector		
Landing Gear		
Prop Pitch		
Trims		

Date received by Operations Manager_____

Note: Pictorial sketches of special equipment should accompany this
      form.

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Figure 6.1.3-2: Control Loader Requirements

PROJECT TITLE_____
PROJECT ENGINEER_____ TELEPHONE_____
OPERATIONS MANAGER_____ TELEPHONE_____
SIMULATOR_____ RIGHT/LEFT SEAT_____
SIMULATOR START DATE_____ (Req. should be in 2 wks. before start date)

CONTROL CONFIGURATION

TYPE CONTROL	PITCH	ROLL		YAW
		WHEEL	STICK	
Travel	Aft___Fwd___ in.	± deg.	± in.	± in.
Control Force (max)	lbs.	lbs.	lbs.	lbs.
Breakout Force Range	lbs.	lbs.	lbs.	lbs.
Basic Force Gradient Range	lb/in	lb/deg	lb/in	lb/in
Max. Force for External Gradient	lb/in	lb/deg	lb/in	lb/in
Variable Force Gradient Yes or No				
External Trim Yes or No				

SPECIAL REQUIREMENTS

ITEM	PITCH	ROLL	YAW
Friction			
Damping Ratio			
Hysteresis			
Trim Rate Range			
Other-Describe			

DOCUMENTATION REQUIREMENTS

    Force vs. Position Plots_____
    Other-Describe_____
    _____

Date received by Control Loader Specialists_____
Project#_____Project Code_____

Figure 6.1.3-3:   Instrumentation Requirements

NEW DIAL FACES

A pictorial sketch of dial faces that are not in the Instrumentation
Handbook should accompany this form. The sketch should contain the
following information:

        a. Size of dial face
        b. Scale
        c. Angular location of graduations on the dial face
        d. All major, minor, etc. scale divisions
        e. All required letters, numbers and symbols and their
           locations.

INSTRUMENT PANEL LAYOUT

A preliminary sketch showing the relative positions of all instruments
on the instrument panel is required. If possible, it should show all
the lights and switches that are to be mounted on the panel.

Circles can be used to show the position of the instruments on the panel.
The type and scale of each instrument should be printed inside each circle.

There are some surplus instrument panels avaliable. The Operations
Manager will provide assistance in showing these panels. A considerable
amount of time can be saved if a surplus panel can be used rather than
to design and fabricate a new one.

SIDEARM CONTROLLER REQUIREMENTS

TYPE	POTENTIOMETER	STRAIN GAGE
1 AXIS		
2 AXIS		
3 AXIS		

OTHER REQUIREMENTS

_____
_____
_____
_____
_____

Date received by Instrument Specialists_____
Project#_____Project Code_____

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Figure 6.1.3-4: Discrete Hardware Requirements

PROJECT TITLE_____
PROJECT ENGINEER_____ TELEPHONE_____
OPERATIONS MANAGER_____ TELEPHONE_____
SIMULATOR_____ RIGHT/LEFT SEAT_____
SIMULATOR START DATE_____ J.O._____

DISCRETE HARDWARE REQUIREMENTS

If the Discrete Hardware Requirements are a part of the Flight Control
Requirements then the same advance notice for Flight Control Hardware
Requirements apply. Normally the Discrete Hardware Requirements should
be in 5 weeks before start date. All lights and switches on instrument
panel should be shown on instrument panel layout drawing.

LIGHTS

How Labeled	Type	Color	Location	Status When On

LIGHT/SWITCH COMBINATION

How Labeled	Type	Color	Location	Switch Function

SWITCHES/BUTTONS

How Labeled	Type	Color	Location	Status When On

SPECIAL CIRCUITS

Special circuits such as audio alarms, stick shakers, etc. should accompany
this form.

Date received by Operations Manager_____

A. General

- Test objectives

- Preliminary test plan indicating expected range of initial conditions and parametric variations

- Static and dynamic check cases

B. Aircraft Model

- Models of aerodynamics, engines, flight control systems, landing gear, winds, and turbulence

- Aircraft weight and moments of inertia

- The location of the cockpit relative to the c.g.

- The locations of sensors (e.g., linear accelerometers and ILS receivers) relative to the c.g.

C. Data Requirements

- Real time data processing requirements

- Data recording: parameters and output format (strip charts, line printer, X-Y plotter, magnetic tape, voice recorder, photographs, etc.)

D. Cockpit

- Control manipulator configuration (see Figure 6.1.3-1 as a guide)

- Control force/displacement characteristics (see Figure 6.1.3-2 as a guide)

- Instrumentation (see Figure 6.1.3-3 as a guide)

- Discrete hardware requirements (see Figure 6.1.3-4 as a guide)

- Head-up display requirements

- Aural simulation: type and number of engines, aural warning devices, etc.

E. Visual Display

- General terrain model requirements (e.g., conventional airport or STOL port)

- Special requirements (e.g., VASI or reduced visibility simulation)

F. Motion System

- Special requirements (e.g., elastic mode simulation)

- Drive logic (if subject of research)

G. Miscellaneous

- Special computer requirements (e.g., IC position or trim calculations)

- Requirements for researcher's station (displays and controls)

- Locations of ground based guidance (e.g., ILS transmitters or VOR stations)

H. Hardware

These requirements refer to researcher-supplied equipment that is part of the test arrangement. It may be elements of the flight control system (such as an airborne computer), special cockpit displays or manipulators, special seats, aural devices, gyro packages, or measurement subsystems.

6.1.4 MANAGEMENT OF TEST AND DIVISION OF RESPONSIBILITY

The responsibility for operation, maintenance, and modification of simulator equipment is assigned to the various groups within the Simulation Sciences Division. One individual, the Program Manager, is assigned the responsibility of interfacing between the researcher and the Simulation Sciences groups that provide support. This person is also responsible for

conduct of the test. In this way communication is enhanced and require-
ments disseminated to the various groups. A summary of this responsibility
follows:

Researcher

- Selection and scheduling of test configurations and pilots

- Briefing and debriefing of pilots

- Data collection and analysis

- Maintaining a run log.

Program Manager (Simulation Sciences Division)

- Hardware operation

- Scheduling of hardware and support personnel

- Hardware maintenance, repair, and performance validation

- Maintaining a hardware log (hardware problems and down time)

It should be noted that support people are directly responsible only
to the program manager and the researcher may resolve problems only through
him.

6.1.5 CONTINGENCY PLANS AND TEST MATRIX

The test matrix is a detailed run description that includes run
number, initial and final conditions, approximate length of time for each
run, equipment to be used, pilot, vehicle configuration, and data to be
acquired.

For the following reasons, the preparation of a contingency plan is
urged:

- Tests proceed faster or slower than expected, e.g.
  the pilot needs more training time

- Hardware availability (up time) may be longer or shorter than expected.

When such occurrences reduce test time available, it is often not possible to reschedule downstream so a re-test period could be made available. A contingency plan for the remaining test time often can achieve most of the test objectives. The ingredients of the contingency plan should include:

- Assignment of priority to test components

- Time for retesting after first examination of test data

- Definition of tests that can be performed with some equipment malfunctions

- Methods of correcting test data in case of equipment failure.

It is reasonable to expect a utilization of 65% where utilization is defined as:

$$100 \times \frac{\text{time equipment is up and available for piloted simulation}}{\text{scheduled occupancy time}}$$

The value is based on an eight hour day (8 to 11:30, 12 to 4:30) and includes average time lost due to:

- Daily setup and checkout procedures

- Down time due to hardware malfunction

- Coefficient and option changes in BASIC software

- Meal breaks for personnel.

This utilization figure can vary with the simulation complexity and is given as a guide to the researcher in structuring the test plan. Other factors may be equally important to overall utilization, i.e., productive runs in the available up time. Some of these factors that contribute to a "time overhead" are:

- Crew changes ($\sim$10 minutes)

- Configuration changes ($\sim$1 to 2 minutes)

- Data readout

- Practice runs

- Visual system initialization.

6.2 CHECKOUT PROCEDURES

Like any complex system, a research flight simulation can be broken down into several elements arranged in series. In a gross sense, inputs are created by the pilot through his controls and outputs from the system are created by the serial combination of the computer and all the downstream components such as the control loaders, instruments, visual displays, and motions. These, in turn, stimulate the pilot and the so-called "closed loop" aspect of manned simulation is created. A basic rule for checkout is that if each component and the interfaces between them is checked out, the system has been checked out also. This is indeed one method. Another is serial, that is, one starts at the front (computer and input interfaces) and proceeds through the system to the end (motion system, etc.). The difficulty with this method is that a "good" test input form for one component does not necessarily produce an output wave form that is appropriate to the testing of the following component. For example, a step of longitudinal stick may produce a washed out trace of normal acceleration which, when applied to the motion system through the drive logic, produces a command waveform that is inefficient to the testing of the motion system. Another difficulty of the serial checkout approach is that the time sequencing for checkout is also serial, thus more time is required to accomplish total checkout.

The component checkout method with a continuity check is preferred because of the time savings. Much of the software can be checked out prior to occupancy. In the case of the control loaders and head-up display, practically independent checkout is possible since the bulk of their

control process is performed by auxiliary (analog and digital) computers. A period of intensive checkout may be required following integration of hardware. A checkout plan should include the checks for the setup phase, the daily checks, and the post-test phase if required. A brief example of a checkout checklist is given in Table 6.2-1.

6.3 OPERATING SUGGESTIONS

Below are listed several suggested operating procedures that could save setup and test time; and reduce the effort required to coordinate the experiment.

1) If a variety of conditions are to be tested, provide optional IC calculations to simplify the changes or use RAD files to change parameters. Examples are:

   - RAD files to define different aircraft characteristics, IC positions, or wind profiles

   - An optional IC routine which, given the initial altitude, computes the X and Y position to center the aircraft on the ILS.

2) Include in the data collection software all performance measures which might be useful in the data analysis

3) Include in the digital printout a complete identification of the test conditions (e.g., date, time, run number, pilot, aircraft configuration, flight control system status, turbulence level, etc.).

4) If there is an appreciable amount of digital output, use the background of the computer for storing these data. Examples would be the line printer, digital tapes, or RAD files. A few key parameters (e.g., touchdown sink rate and position) can also be displayed in real-time using the computer terminal or the foreground printer-plotter.

TABLE 6.2-1

EXAMPLE CHECKOUT LIST

FREQUENCY	ITEM	CHECKOUT METHODS
One time	Aircraft Model	
	Statics	Compare trim conditions with researcher's data
	Dynamics	Compare stability derivatives and responses to simple inputs with researcher's data
One time	Engine Dynamics	Compare step responses with researcher's data
One time	Flight Control System	Compare responses to simple inputs with researcher's data
		Determine parameter values for neutral stability and limit cycle frequency; compare with researcher's data
One time	Control Loaders	
	Statics	Compare force/displacement plots with researcher's requirements
	Dynamics	Compare response to force command with researcher's data
Daily	Manipulators	Check sign and magnitude of signal in digital computer for various deflections
Daily	Cockpit Discretes	Check continuity between cab and digital computer
Daily	Cockpit Instruments	Check instrument scale and bias
	Visual System	
Daily	Statics	Check static position and orientation of pilot's monitor (if landings are to be simulated, check for position near nominal touchdown point)
One time	Dynamics	Do visual SAFE
		Monitor follow-up errors for nominal run
Daily	Optical Properties	Observe picture quality from pilot's monitor
One time	Motion System	Do motion SAFE
Daily		Run motion dynamic check
One time	Data Collection	Cross check data from different sources, e.g., line-printer output versus strip chart recorder
One time	Researcher's Controls and Displays	For discretes, check continuity between each element and computer. For continuous I/O, cross check magnitude and sign between each element and digital computer

VI-15

5) Include as part of the last portion of the setup and checkout period, a brief validation phase whose intent is to establish overall fidelity.

6) Work with the computer programmer to make sure that all elements of the simulation are optimized. An example might be cycle time problems. A number of elements might be dropped from the generalized BASIC simulation system to reduce cycle time (landing gear, turbulence, wind, etc.).

7) Use CASPRE setup decks to store the trim states for various flight conditions. This will eliminate the use of a trim routine every time a flight condition is changed.

6.4 TROUBLE SHOOTING DIAGNOSTIC TOOLS

Included among the software and hardware of the FSAA facility are several tools that can be used to diagnose problems.

1) Step inputs normally can be applied to variables within the system models.

2) The SAFE (Six-Axes Frequency Evaluation) subroutine which can be applied to the control loaders, visual system, and motion system is a method of evaluating the sinusoidal response and noise of any of these systems in an automated way. SAFE was described in detail in Section 5 (Motion System).

3) Several low-frequency wave analyzers may be used for evaluating input-output relations of any component capable of accepting and transmitting analog voltages.

4) The laboratory is also well-stocked with strip chart recorders, X-Y plotters, and oscilloscopes that can be quickly interfaced to virtually any piece of equipment.

APPENDIX A

EQUATIONS OF MOTION USED BY BASIC

This appendix summarizes the equations of motion used by BASIC. Their derivation is discussed in detail in Reference 5.

A.1 NOMENCLATURE

A.1.1 SYMBOLS

C_i Coefficients of moment of inertia

C_i' Coefficients of angular momentum of rotating machinery

F Total force acting on the aircraft, lb

h Altitude above sea level, ft

h_x, h_y, h_z X, Y, and Z components of angular momentum of rotating machinery, slug-ft^2/sec

I_{XX} Moment of inertia about the X axis, slug-ft^2

I_{YY} Moment of inertia about the Y axis, slug-ft^2

I_{ZZ} Moment of inertia about the Z axis, slug-ft^2

I_{XZ} Product of inertia

L, M, N Total applied torques acting on the aircraft about the X, Y, and Z axes, ft-lb

m Mass of the aircraft, slugs

p, q, r Angular rates about the X, Y, and Z axes, respectively, rad/sec

A-1

R	Radius of earth plus altitude of aircraft, ft
t	Time, sec
T_{ij}	Transformation matrix from the local to body axes
V	Linear velocity, ft/sec
λ	Aircraft latitude, rad
Ψ,Θ,Φ	Euler angles, rad
τ	Aircraft longitude, rad
ω_e	Angular velocity of the earth, rad/sec

A.1.2 FORTRAN NAMES

The Fortran names used in this appendix are defined in Table B-1.

A.1.3 SUBSCRIPTS

B	Aircraft body axes
D	Down
E	East
G	Gravity
L	Local axes
N	North

A.2 AXIS SYSTEMS

A.2.1 LOCAL AXES, L

The local axis system is located on the surface of the earth (sea level), and directly under the aircraft. X_L points north, Y_L points east, and Z_L points towards the center of the earth.

A-2

A.2.2 BODY AXES, B

The center of the body axes is located at the center of gravity of the aircraft. X_B points forward along the fuselage reference line, Y_B points out the right wing, and Z_B points out the bottom of the aircraft. X_B and Z_B are in the aircraft plane of symmetry. The orientation of the B-axes wrt the L-axes is specified by the usual Euler angles, Ψ, Θ, and Φ.

A.3 LINEAR ACCELERATION

The linear acceleration of the aircraft center of gravity can be expressed in the local axes system as follows:

$$\begin{bmatrix} VND \\ VED \\ VDD \end{bmatrix} = \frac{1}{m} \begin{bmatrix} F_N \\ F_E \\ F_D + F_G \end{bmatrix} + \frac{1}{R} \begin{bmatrix} V_N V_D - V_E^2 Tan\lambda \\ V_E V_D + V_N V_E Tan\lambda \\ -(V_N^2 + V_E^2) \end{bmatrix} \qquad \text{A-1a}$$

When the flat earth option is used the expression is:

$$\begin{bmatrix} VND \\ VED \\ VDD \end{bmatrix} = \frac{1}{m} \begin{bmatrix} F_N \\ F_E \\ F_D + F_G \end{bmatrix} \qquad \text{A-1b}$$

A.4 LINEAR VELOCITY

The inertial velocity of the aircraft in local axes is then

$$\begin{bmatrix} VN \\ VE \\ VD \end{bmatrix} = \int \begin{bmatrix} VND \\ VED \\ VDD \end{bmatrix} dt \qquad \text{A-2}$$

To obtain the velocity relative to the earth's surface, it is necessary to correct only the easterly component.

$$VEE = VE - R\omega_e \cos\lambda \qquad \text{A-3a}$$

When the flat earth option is used

$$VEE = VE \qquad \text{A-3b}$$

A.5 POSITION

The position of the aircraft c.g. wrt the surface of the earth is then

$$\begin{bmatrix} \tau \\ \lambda \\ h \end{bmatrix} = \begin{bmatrix} XLON \\ XLAT \\ ALT \end{bmatrix} = \int \begin{bmatrix} \dot{\tau} \\ \dot{\lambda} \\ -VD \end{bmatrix} at \qquad \text{A-4}$$

where,

$$\begin{bmatrix} \dot{\tau} \\ \dot{\lambda} \end{bmatrix} = \frac{1}{R} \begin{bmatrix} VEE/\cos\lambda \\ VN \end{bmatrix} \qquad \text{A-5}$$

Position wrt the runway is computed from the runway heading and differences in aircraft and runway longitude, latitude, and altitude.

A.6 ANGULAR ACCELERATION

An expression for the angular acceleration of the aircraft body axis wrt inertial space can be obtained from Euler's equations. If it is assumed that the X-Y and Y-Z products of inertias are zero,

$$\begin{bmatrix} PBD \\ QBD \\ RBD \end{bmatrix} = \begin{bmatrix} (C_1 r_B + C_2 p_B)q_B \\ C_5 p_B r_B + C_6(r_B^2 - p_B^2) \\ (C_8 p_B + C_9 r_B)q_B \end{bmatrix} + \begin{bmatrix} C_3 & 0 & C_4 \\ 0 & C_7 & 0 \\ C_4 & 0 & C_{10} \end{bmatrix} \begin{bmatrix} L \\ M \\ N \end{bmatrix} + \begin{bmatrix} -C_6' & C_1' & C_5' \\ C_3' & 0 & -C_2' \\ -C_7' & C_4' & C_6' \end{bmatrix} \begin{bmatrix} p_B \\ q_B \\ r_B \end{bmatrix} \qquad \text{A-6}$$

The coefficients used in Equation A-6 are computed from the moments of inertia and the angular momentum of rotating machinery. They are defined in equations A-7 and A-8.

$$
\begin{bmatrix} c_0 \\ c_1 \\ c_2 \\ c_3 \\ c_4 \\ c_5 \\ c_6 \\ c_7 \\ c_8 \\ c_9 \\ c_{10} \end{bmatrix}
=
\begin{bmatrix}
(I_{XX}I_{ZZ}-I_{XZ}^2)^{-1} \\
c_0\left\{(I_{YY}-I_{ZZ})I_{ZZ}-I_{XZ}^2\right\} \\
c_0 I_{XZ}(I_{XX}-I_{YY}+I_{ZZ}) \\
c_0 I_{ZZ} \\
c_0 I_{XZ} \\
c_7(I_{ZZ}-I_{XX}) \\
c_7 I_{XZ} \\
I_{YY}^{-1} \\
c_0\left\{(I_{XX}-I_{YY})I_{XX}+I_{XZ}^2\right\} \\
c_0 I_{XZ}(I_{YY}-I_{ZZ}-I_{XX}) \\
c_0 I_{XX}
\end{bmatrix}
\qquad \text{A-7}
$$

A-5

$$
\begin{bmatrix} c_1' \\ c_2' \\ c_3' \\ c_4' \\ c_5' \\ c_6' \\ c_7' \end{bmatrix} = \begin{bmatrix} C_0(I_{XZ}h_X - I_{ZZ}h_Z) \\ C_7 h_X \\ C_7 h_Z \\ C_0(I_{XX}h_X - I_{XZ}h_Z) \\ C_0 I_{ZZ} h_Y \\ C_0 I_{XZ} h_Y \\ C_0 I_{XX} h_Y \end{bmatrix} \qquad \text{A-8}
$$

A.7 ANGULAR VELOCITY

The angular velocity of the aircraft body axis wrt inertial space is

$$
\begin{bmatrix} PB \\ QB \\ RB \end{bmatrix} = \int \begin{bmatrix} PBD \\ QBD \\ RBD \end{bmatrix} dt \qquad \text{A-9}
$$

The angular velocity of the local axis system wrt inertial space can be expressed in local axis components as

$$
\begin{bmatrix} PL \\ QL \\ RL \end{bmatrix} = \frac{1}{R} \begin{bmatrix} V_E \\ -V_N \\ -V_E \tan\lambda \end{bmatrix} \qquad \text{A-10a}
$$

If the flat earth option is used

$$
\begin{bmatrix} PL \\ QL \\ RL \end{bmatrix} = 0 \qquad \text{A-10b}
$$

The angular velocity of the local axes can be resolved into the aircraft body axis by

$$
\begin{bmatrix} PLB \\ QLB \\ RLB \end{bmatrix} = [T_{ij}] \begin{bmatrix} PL \\ QL \\ RL \end{bmatrix}
$$
A-11

The angular velocity of the aircraft body axes wrt the local axes is thus

$$
\begin{bmatrix} PT \\ QT \\ RT \end{bmatrix} = \begin{bmatrix} PB \\ QB \\ RB \end{bmatrix} - \begin{bmatrix} PLB \\ QLB \\ RLB \end{bmatrix}
$$
A-12

A·8 EULER ANGLES

The angular position of the aircraft body axes wrt the local azes is specified by the usual Euler angles. The rate of change of the Euler angles is related to the relative angular velocity as follows:

$$
\begin{bmatrix} \dot{\Psi} \\ \dot{\Theta} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} (q_T \sin\phi + r_T \cos\phi)\sec\Theta \\ q_T \cos\phi - r_T \sin\phi \\ p_T + \dot{\Psi}\sin\Theta \end{bmatrix}
$$
A-13

The Euler angles are

$$
\begin{bmatrix} \Psi \\ \Theta \\ \phi \end{bmatrix} = \int \begin{bmatrix} \dot{\Psi} \\ \dot{\Theta} \\ \dot{\phi} \end{bmatrix} dt
$$
A-14

APPENDIX B

BASIC COMMON

Tables B-1 and B-2 define the contents of the BASIC common. Table B-1 define the variables in the floating point common, XFLOAT. Table B-2 define the variables in the fixed point common, IFIXED.

TABLE B-1

LIST AND DESCRIPTION OF BASIC FLOATING POINT COMMON, XFLOAT

COMMON NUMBER	VARIABLE	FORTRAN NAME	UNITS	ORIGIN AND/OR DEFAULT VALUE	DESCRIPTION
1	ϕ	PHI	deg	BROTATE	Aircraft Euler angles in degrees and radians.
2	θ	THET	deg		
3	ψ	PSI	deg		
4	ϕ	PHIR	rad		
5	θ	THETR	rad		
6	ψ	PSIR	rad		
7	$\dot\phi$	PHID	rad/sec		Aircraft Euler angle rates.
8	$\dot\theta$	THED	rad/sec		
9	$\dot\psi$	PSID	rad/sec		
10	$\sin\phi$	SPHI	ND	BTRANSFO	Sines and cosines of all aircraft Euler angles.
11	$\cos\phi$	CPHI	ND		
12	$\sin\theta$	STHT	ND		
13	$\cos\theta$	CTHT	ND		
14	$\sin\psi$	SPSI	ND		
15	$\cos\psi$	CPSI	ND		
16		T11	ND		Components of the Local-to-Body axes transformation matrix, i.e., $$\vec{V}_B = [\tau_{ij}]\,\vec{V}_L$$
17		T21	ND		
18		T31	ND		
19		T12	ND		
20	τ_{ij} =	T22	ND		
21		T32	ND		
22		T13	ND		
23		T23	ND		
24		T33	ND		
25	α	ALFA	deg	BALFBET	Angles of attack and sideslip in degrees and radians.
26	β	BETA	deg		
27	α	ALFAR	rad		
28	β	BETAR	rad		
29	$\dot\alpha$	ALFD	rad/sec		Angular rates of angles of attack and sideslip.
30	$\dot\beta$	BETD	rad/sec		

B-2

COMMON NUMBER	VARIABLE	FORTRAN NAME	UNITS	ORIGIN AND/OR DEFAULT VALUE	DESCRIPTION
31	$\sin \alpha$	SALPH	ND	BALFBET	
32	$\cos \alpha$	CALPH	ND		Sines and cosines of angles of attack and sideslip.
33	$\sin \beta$	SBETA	ND		
34	$\cos \beta$	CBETA	ND		
35	γ_V	GAMV	rad	BINERTIA	Inertial flight path angles in the vertical and horizontal planes. γ_H positive clockwise from North.
36	γ_H	GAMH	rad		
37		PB	rad/sec	BROTATE	
38	$\vec{\omega}_{B_I} =$	QB	rad/sec		Body axis components of the aircraft angular velocity wrt inertial space.
39		RB	rad/sec		
40		PL	rad/sec	BINERTIA	
41	$\vec{\omega}_{F_L} =$	QL	rad/sec		
42		RL	rad/sec		Local and body axes components of the angular velocity of the local coordinate system wrt inertial space.
43		PLB	rad/sec		
44	$\vec{\omega}_{F_B} =$	QLB	rad/sec		
45		RLB	rad/sec		
46		PT	rad/sec	BROTATE	Body axis components of the angular velocity wrt the Earth, i.e.,
47	$\vec{\omega}_{B_L} =$	QT	rad/sec		$\vec{\omega}_{B_L} = \vec{\omega}_{B_I} - \vec{\omega}_{F_L}$
48		RT	rad/sec		
49		PBWN	rad/sec		Body axis components of the aircraft angular velocity wrt inertial space plus an equivalent angular velocity due to turbulence, i.e., $\vec{\omega}_{BN_I} = \vec{\omega}_{B_I} + \vec{\omega}_N$
50	$\vec{\omega}_{BN_I} =$	QBWN	rad/sec		
51		RBWN	rad/sec		(used in computing aerodynamic forces and moments)
52		PTURB	rad/sec	BWIND	Body axis components of the equivalent angular velocity due to atmospheric turbulence (gust gradient effects).
53	$\vec{\omega}_N =$	QTURB	rad/sec		
54		RTURB	rad/sec		
55		PBD	rad/sec^2	BROTATE	Body axis components of the aircraft angular acceleration wrt inertial space.
56	$\dot{\vec{\omega}}_{B_I} =$	QBD	rad/sec^2		
57		RBD	rad/sec^2		
58		UB	ft/sec	BVELOCIT	Body axis components of the aircraft velocity wrt the air mass.
59		VB	ft/sec		
60		WB	ft/sec		

COMMON NUMBER	VARIABLE	FORTRAN NAME	UNITS	ORIGIN AND/OR DEFAULT VALUE	DESCRIPTION
61		UTURB	ft/sec	BWIND	Body axis components of the linear velocity due to atmospheric turbulence. (Positive for gust in positive X, Y, or Z direction).
62		VTURB	ft/sec		
63		WTURB	ft/sec		
64		VN	ft/sec	BHORIZON	Local axis components of the aircraft velocity wrt inertial space.
65		VE	ft/sec		
66		VD	ft/sec	BVERTICA	
67		VEE	ft/sec	BHORIZON	Eastward component of the aircraft velocity wrt the earth's surface.
68		VT	ft/sec	BINERTIA	Magnitude of velocity wrt earth's surface, $VT = \sqrt{VN^2 + VEE^2 + VD^2}$
69		VG	ft/sec		Ground speed. Magnitude of horizontal velocity wrt earth's surface, $VG = \sqrt{VN^2 + VEE^2}$
70		VRW	ft/sec	BALFBET	Airspeed, magnitude of velocity wrt air mass.
71	M	XMACH	ND	BATMOSPH	Mach number.
72		VNR	ft/sec	BVELOCIT	Local axis components of the aircraft velocity wrt the air mass.
73		VER	ft/sec		
74		VDR	ft/sec		
75	V_{eq}	VEQ	kt	BATMOSPH	Equivalent airspeed.
76		VNW	ft/sec	WINDC,0.	North, east, and down components of the wind (positive for wind blowing to north, east, or down)
77		VEW	ft/sec		
78		VDW	ft/sec		
79		VTW	ft/sec		Magnitude of wind.
80	$\dot{h}$	ALTD	ft/sec	BVERTICA	Altitude rate, $\dot{h} = -VD$.
81	$\dot{\tau}$	XLOND	rad/sec	BHORIZON	Rate of change of aircraft longitude.
82	$\dot{\lambda}$	XLATD	rad/sec		Rate of change of aircraft latitude.
83	h	ALT	ft	BVERTICA	Altitude of aircraft wrt sea level.
84	τ	XLON	rad	BHORIZON	Aircraft longitude.
85	λ	XLAT	rad		Aircraft latitude.
86	sin λ	SLAT	ND	BEARTH	Sine of aircraft's latitude.
87	cos λ	CLAT	ND		Cosine of aircraft's latitude.

COMMON NUMBER	VARIABLE	FORTRAN NAME	UNITS	ORIGIN AND/OR DEFAULT VALUE	DESCRIPTION
88		VND	ft/sec^2	BHORIZON	Derivatives of local axis components of aircraft velocity wrt inertial space.
89		VED	ft/sec^2		
90		VDD	ft/sec^2	BVERTICA	
91	$\vec{A}_{cg} =$	AX	ft/sec^2	BACCELER	Body axis components of specific force (accelerometer output) at the aircraft's cg.
92		AY	ft/sec^2		
93		AZ	ft/sec^2		
94	$\vec{A}_{pilot} =$	AXP	ft/sec^2		Body axis components of specific force at the pilot station.
95		AYP	ft/sec^2		
96		AZP	ft/sec^2		
97	g	G	ft/sec^2	BEARTH	Acceleration due to gravity, 32.2 at h=0.
98		XDDS	ft/sec^2	0.	Reserved for simulator drives (i.e., the researcher could supply commands different from those calculated by BBEND).
99		YDDS	ft/sec^2	0.	
100		ZDDS	ft/sec^2	0.	
101	V_c	VCAL	kt	BATMOSPH	Calibrated airspeed.
102		HWEEL	ft	BVERTICA	Approximate height of main gear above runway.
103		XPR	ft	BHORIZON	Distance of pilot down the runway.
104		YPR	ft		Distance of pilot to the right of the runway.
105		HPR	ft		Height of pilot above the runway.
106		DNR	ft		Northward and Eastward distance of the aircraft c.g. from the runway threshold.
107		DER	ft		
108		RR	ft	BSETUP	Radius of earth plus altitude of runway (HR).
109		RTV	ft	BEARTH	Radius of earth plus altitude of aircraft (ALT).
110	θ_R	THETRR	deg	90.	Runway heading from North (cockwise position).
111	λ_R	XLATR	rad	0.	Latitude of the runway.
112	l_R	XLONR	rad	0.	Longitude of the runway.
113	$\cos \lambda_R$	CLATR	ND	BSETUP	Cosine of the runway latitude.

COMMON NUMBER	VARIABLE	FORTRAN NAME	UNITS	ORIGIN AND/OR DEFAULT VALUE	DESCRIPTION
114	$\sin \theta_R$	STHETR	ND	BSETUP	Sine and cosine of the runway heading.
115	$\cos \theta_R$	CTHETR	ND		
116	I_X	XIXX	slug-ft^2		Moments and product of inertia in the aircraft body axis.
117	I_Y	XIYY	slug-ft^2		
118	I_Z	XIZZ	slug-ft^2		
119	I_{XZ}	XIXZ	slug-ft^2		
120		XMC1	ND		
121		XMC2	ND		
122		XMC3	slug^{-1}-ft^{-2}		
123		XMC4	slug^{-1}-ft^{-2}		
124	c_i =	XMC5	ND		Moment of inertia coefficients used to compute angular accelerations. Definitions are contained in Appendix A.
125		XMC6	ND		
126		XMC7	slug^{-1}-ft^{-2}		
127		XMC8	ND		
128		XMC9	ND		
129		XMC10	slug^{-1}-ft^{-2}		
130	m	XMASS	slug		Aircraft mass.
131	c_L	CL	ND	AERO2	Lift and drag coefficients (stability axis)
132	c_D	CD	ND		
133	c_X	CX	ND		Non-dimensional force coefficients (body axis).
134	c_Y	CY	ND		
135	c_Z	CZ	ND		
136		FAX	lb		Body axis components of the aerodynamic forces.
137	$\vec{F}_A$ =	FAY	lb		
138		FAZ	lb		
139		FEX	lb	ENGINE	Body axis components of the applied forces due to the engines.
140	$\vec{F}_E$ =	FEY	lb		
141		FEZ	lb		

COMMON NUMBER	VARIABLE	FORTRAN NAME	UNITS	ORIGIN AND/OR DEFAULT VALUE	DESCRIPTION
142	$\vec{F}_G$ =	FGX	lb	BLGC	Body axis components of the applied forces due to the landing gear.
143		FGY	lb		
144		FGZ	lb		
145	$\vec{F}_T$ =	FTX	lb	BFTOTAL	Sum of forces due to aerodynamic loads, the engines, and the landing gear.
146		FTY	lb		
147		FTZ	lb		
148	$\vec{F}_{T_E}$ =	FN	lb	BHORIZON	$\vec{F}_{T_E} = [T_{ij}]^T \vec{F}_T$ = the local axis components of the total applied force acting on the aircraft.
149		FE	lb		
150		FD	lb	BVERTICA	
151		FG	lb	BEARTH	Force due to gravity, mg, at altitude ALT.
152	C_ℓ	CLL	ND	AERO2	Coefficients of aerodynamic rolling, pitching, and yawing moments.
153	C_m	CLM	ND		
154	C_n	CLN	ND		
155	$\vec{T}_A$ =	TAL	ft-lb		Body axis components of the applied torque due to aerodynamic loads.
156		TAM	ft-lb		
157		TAN	ft-lb		
158	$\vec{T}_E$ =	TEL	ft-lb	ENGINE	Body axis components of the applied torque due to the engines.
159		TEM	ft-lb		
160		TEN	ft-lb		
161	$\vec{T}_G$ =	TGL	ft-lb	BLGC	Body axis components of the applied torque due to the landing gear.
162		TGM	ft-lb		
163		TGN	ft-lb		
164	$\vec{T}_T$ =	TTL	ft-lb	BTORQUE	Sum of torques due to aerodynamic loads, the engines, and the landing gear.
165		TTM	ft-lb		
166		TTN	ft-lb		
167	Δt_1	DT1	sec	ECETUP	First loop frame time = IDT1/1000.
168	Δt_2	DT2	sec		Second loop frame time = N2*DT1.
169	Δt_3	DT3	sec		Third loop frame time = N3*DT1.
170	h_R	HR	ft	0.	Altitude of runway wrt sea level.

COMMON NUMBER	VARIABLE	FORTRAN NAME	UNITS	ORIGIN AND/OR DEFAULT VALUE	DESCRIPTION
171		XP	ft	87.	Coordinates of the pilot in aircraft body axes.
172		YP	ft	0.	
173		ZP	ft	-2.75	
174		XCG	ft	BEARTH	Coordinates of the aircraft c.g. wrt the runway axis system.
175		YCG	ft	↓	
176		HCG	ft	BVERTICA	
177	W	WAIT	lb	BSETUP	Weight of aircraft at sea level (g $\triangleq$ 32.2).
178	$\bar{q}$	QBAR	lb/ft^2	BATMOSPH	Dynamic pressure.
179	$\bar{q}_c$	QBARC	lb/ft^2	↓	Impact pressure.
180	S	AREA	ft^2	0.	Wing area.
181	b	SPAN	ft	0.	Wing span.
182	$\bar{c}$	CHORD	ft	27.66	Wing mean aerodynamic chord.
183	ρ	RHO	slug/ft^3	BATMOSPH	Air density at altitude ALT.
184		XTAIL	ft	-63.2	Coordinates of the aircraft tail wrt the aircraft body axis system.
185		ZTAIL	ft	1.07	
186		HTAIL	ft	BLGA	Height of tail above runway.
187		XNG	ft	50.	Coordinate of the nose gear wrt the aircraft body axis system.
188		YNG	ft	0.	
189		ZNG	ft	16.3	
190		XRG	ft	-5.0	Coordinate of the right main gear wrt the aircraft body axis system.
191		YRG	ft	12.6	
192		ZRG	ft	14.58	
193		XLG	ft	-5.0	Coordinate of the left main gear wrt the aircraft body axis system.
194		YLG	ft	-12.6	
195		ZLG	ft	14.58	
196		XOE	ft	0.	Coordinates of the right wing outboard engine wrt the aircraft body axis system.
197		YOE	ft	20.0	
198		ZOE	ft	0.	

COMMON NUMBER	VARIABLE	FORTRAN NAME	UNITS	ORIGIN AND/OR DEFAULT VALUE	DESCRIPTION
199		XIE	ft	0.	Coordinates of the right wing inboard engine wrt the aircraft body axis system.
200		YIE	ft	15.8	
201		ZIE	ft	0.	
202		HTAILD	ft/sec	BLGA	Rate of change of tail height.
203		DSTN	ft		Gear strokes for nose, right and left gear. (Negative for oleo compression).
204		DSTR	ft		
205		DSTL	ft		
206		DSTND	ft/sec		Gear stroke rates for nose, right and left gear.
207		DSTRD	ft/sec		
208		DSTLD	ft/sec		
209	a	SOUND	ft/sec	BATMOSPH	Speed of sound at altitude ALT.
210		FOLEO1	lb	GEARS	Oleo forces on aircraft due to the nose, right and left gears (normal to runway, positive down).
211		FOLEO2	lb		
212		FOLEO3	lb		
213		FRICT1	lb		Friction forces on aircraft due to the nose, right and left gears (parallel to runway, positive forward).
214		FRICT2	lb		
215		FRICT3	lb		
216		FSIDE1	lb		Side forces on aircraft due to the nose, right and left gears (ground plane, positive right).
217		FSIDE2	lb		
218		FSIDE3	lb		
219		FRXP1	lb	BLGB	
220		FRXP2	lb		
221		FRXP3	lb		
222		FRYP1	lb		Body axis components of the total landing gear forces on the nose, right and left gears.
223		FRYP2	lb		
224		FRYP3	lb		
225		FRZP1	lb		
226		FRZP2	lb		
227		FRZP3	lb		

COMMON NUMBER	VARIABLE	FORTRAN NAME	UNITS	ORIGIN AND/OR DEFAULT VALUE	DESCRIPTION
228		FRTAIL	lb	GEARS	Normal and drag forces on aircraft due to a tail strike (positive down and forward).
229		FRICTT	lb	↓	
230	ϕ_{ic}	PHIIC	deg	0.	
231	θ_{ic}	THETIC	deg	0.	Initial values of the aircraft Euler angles.
232	Ψ_{ic}	PSIIC	deg	90.	
233	$\gamma_{V_{ic}}$	GAMVIC	deg	0.	Initial conditions of inertial flight path angles in the vertical and horizontal planes.
234	$\gamma_{H_{ic}}$	GAMHIC	deg	90.	
235		PBIC	deg/sec	0.	Initial conditions of the body axis components of the aircraft angular velocity wrt inertial space.
236		QBIC	deg/sec	0.	
237		RBIC	deg/sec	0.	
238	V_{eq}	VEQIC	kt	150.	Initial condition of the equivalent airspeed.
239		XIC	ft	-7000.	Initial condition of either the pilot or aircraft c.g. wrt the runway axis system (ICG = 0 or 1).
240		YIC	ft	0.	
241		HIC	ft	500.	
242	W_{ic}	WAITIC	lb	209128.	Initial condition of aircraft weight.
243	$I_{x_{ic}}$	XIXXIC	slug-ft^2	1193151.7	
244	$I_{Y_{ic}}$	XIYYIC	slug-ft^2	9891068.3	Initial conditions of the moments and product of inertia.
245	$I_{Z_{ic}}$	XIZZIC	slug-ft^2	10888744.5	
246	$I_{XZ_{ic}}$	XIXZIC	slug-ft^2	-213555.	
247		XREDCO	volts	BVISUAL	Linear position commands to the Redifon servos.
248		YREDCO	volts	↓	
249		HREDCO	volts		
250		XREDFU	volts	ADC	Redifon follow-ups from position pots for X, Y, and H.
251		YREDFU	volts	ADC	
252		HREDFU	volts	ADC	
253		PHIRED	volts	BVISUAL	Angular position commands to the Redifon servos.
254		THTRED	volts	↓	
255		PSIRED	volts		
256		CG	%	51.4	Location of aircraft c.g. wrt the leading edge of the MAC.

COMMON NUMBER	VARIABLE	FORTRAN NAME	UNITS	ORIGIN AND/OR DEFAULT VALUE	DESCRIPTION
257		XREC	ft	INS10B	Variable sensitivity values of XCG and HCG used for the strip chart recorders (see discussion at INS10B).
258		HREC	ft		
259	ϵ_{GS}	EPSGS	deg		Glide slope error (positive for aircraft high).
260	ϵ_{LOC}	EPSLOC	deg		Localizer error (positive for aircraft to the right).
261		HDOTI	volts		Command signal to the cab IVSI.
262		RSCALE	ND	600.	Redifon model scene scale factor.
263		XZRED	ft	0.	
264		YZRED	ft	0.	X, Y, and H biases for the Redifon.
265		HZRED	ft	0.	
266		VFINE	kt	INS10B	Variable limit values of V_c and HCG used for the strip chart recorders (see discussion at INS10B).
267		HFINE	ft		
268		HRADIO	volts		Command signal to the cab radio altimeter.
269		VIASI	volts		Command signal to the cab calibrated airspeed instrument.
270		TUP	deg	-.5	Orientation of pilot's viewing angle wrt the aircraft body axis (but normally used for pitch and heading biases for the Redifon servos).
271		TRITE	deg	3.	
272		XPGS	ft	1000.	X and Y coordinates of the glide slope transmitter wrt the runway axis.
273		YPGS	ft	0.	
274		THETGS	deg	2.65	Angle of the glide slope transmitter (positive up).
275		XPLOC	ft	13200.	X and Y coordinates of the localizer transmitter wrt the runway axis.
276		YPLOC	ft	0.	
277		AMEG	deg	27.25	Half angle of outer and middle markers.
278		XOM	ft	-26400.	
279		YOM	ft	0.	Coordinates of the outer and middle markers wrt the runway axis system.
280		XMM	ft	-3500.	
281		YMM	ft	0.	
282		SPEED	mm/sec	INS10B	Speed of strip chart recorders.
283		HFLARE	ft	0.	Flare initiation altitude (see IFLARE).
284		HSEL	ft	AJC	Optional selective altitude (set from Cab).

COMMON NUMBER	VARIABLE	FORTRAN NAME	UNITS	ORIGIN AND/OR DEFAULT VALUE	DESCRIPTION
285		- - -			Not used.
286		DIST35	ft	0.	X-distance to 35 foot obstacle clearance plane.
287	σ_u	UDISP	ft/sec	WINDC	RMS levels of the u and w components of the turbulence.
288	σ_w	WDISP	ft/sec		
289	L_u	UAL	ft		Scale lengths used by the MIL-F-8785 turbulence model.
290	L_w	WAL	ft		
291	σ	DISP	ft/sec	0.	RMS level of the turbulence.
292		- - -			Not used.
293		- - -			Not used.
294		CGZER	%	51.4	Initial and incremental values of the aircraft c.g. wrt the leading edge of the MAC.
295		CGDELT	%	0.	
296		DME	ft	INS10B	Distance from the glide slope source to the pilot.
297		XBLOC	ft	0.	Coordinates of the localizer receiver wrt the aircraft axis system.
298		YBLOC	ft	0.	
299		ZBLOC	ft	0.	
300		XBGS	ft	0.	Coordinates of the glide slope receiver wrt the aircraft axis system.
301		YBGS	ft	0.	
302		ZBGS	ft	0.	
303	t	TIME	sec	RROTATE	Time from start of Operate.
304		HFOGB	ft	700.	Fog ceiling (clear below HFOGB).
305		- - -			
306		FLEVEL	volts	BVISUAL	Command signal to fog generating equipment.
307		- - -			
308		SCSPDA	mm/sec	2.	SPEED=Speed of strip chart recorder= { SCSPDA for ALT<HTSCSW, SCSPDB for ALT>HTSCSW }
309		SCSPDB	mm/sec	5.	
310		HTSCSW	ft	200.	
311		DTD	sec	2.	Duration of dynamic check pulse.
312		TEND	sec	25.	End time of dynamic response sequence.

COMMON NUMBER	VARIABLE	FORTRAN NAME	UNITS	ORIGIN AND/OR DEFAULT VALUE	DESCRIPTION
313		DCVAL1	-	3.2	
314		DCVAL2	-	9.55	Amplitudes of dynamic check inputs 1, 2, and 3.
315		DCVAL3	-	4.27	
316		PTCHDT	volts	0.	
317		RUDROT	volts	0.	Optional command signals to a pitch, rudder, and left and right elevon instruments.
318		ELVLOT	volts	0.	
319		ELVROT	volts	0.	
320		GUTIM	sec	12.	Landing up and down transit times.
321		GDTIM	sec	1.	
322		VSIN	ND	INS10B	
323		VCOS	ND		Command signals to an optional velocity meter.
324		VLSIN	ND		
325		VLCOS	ND		
326		GGAIN1	ND	0.	
327		GGAIN2	ND	0.	Gains used by an optional runway rumble model.
328		GGAIN3	ND	0.	
329		GGAIN4	ND	0.	
330		VIAS3	volts	INS10B	Command signal to PEC calibrated airspeed instrument.
331		HTSELR	ft	0.	Minimum decision altitude.
332		TR	ND	BATMOSPH	Ratio of total to ambient temperature.
333		PR	ND		Ratio of total to ambient pressure.
334		VIAS2	volts	INS10B	Command signal to co-pilot's calibrated airspeed instrument.
335		- - -			
336		- - -			
337		- - -			
338		- - -			Not used.
339		- - -			
340		- - -			
341		- - -			

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COMMON NUMBER	VARIABLE	FORTRAN NAME	UNITS	ORIGIN AND/OR DEFAULT VALUE	DESCRIPTION
342		- - -			
343		- - -			Not used.
344		- - -			
345		- - -			
346		PHIOFF	deg	0.	Roll bias used by the Redifon.
347		- - -			Not used.
348		TRISE	sec	0.	Rise and fall times used by the dynamic
349		TFALL	sec	0.	check program.
350		CGINS	volts	INS10B	Command signal to c.g. instrument
351		- - -			Not used.
352		- - -			Not used.
353		HSIDF	volts	INS10A	Command signal to the HSI.
354		VCLLIM	volts	UTIL3	Command to velocity limit instrument (optional).
355		XMREC	ft	UTIL3	Reserved alternate method of recording X on strip chart recorder.
356		TAU	sec	0.	Time constant of first order lag used to drive the Redifon during IC.
357		- - -			Not used.
358		DCR	rad/deg	0.01745329	Used to convert from degrees to radians.
359		RCD	deg/rad	57.295779	Used to convert from radians to degrees.
360		ZNZE1	ND	EWIND, 1.54237	
361		ZNZE2	ND	EWIND, 3.52431	Starting values used by random noise sources of the MIL-F-8785 turbulence
362		ZNZE3	ND	EWIND, 0.72757	model.
363		ZNZE4	ND	EWIND, 0.55550	
364	ρ_o	RHOZ	slug/ft^3	DATM SBH	Density at sea level, standard day.
365		HRHOZ	ft		Altitude used to calculate ρ if ICOND=1 (constant density).
366	T	TAMB	deg K		Ambient temperature.
367	P	PAMB	lb/ft^2		Ambient pressure.
368	T_t	TTOT	deg K		Total temperature.
369	P_t	PTOT	lb/ft^2		Total pressure.
370		DELAT	deg K	0.	Incremental ambient temperature (optional).

COMMON NUMBER	VARIABLE	FORTRAN NAME	UNITS	ORIGIN AND/OR DEFAULT VALUE	DESCRIPTION
371		VIAS5	volts	INS10B	Command signal to copilot's airspeed instrument.
372		PHIFU	volts	ADC	Redifon follow-ups from position pots for ϕ, θ, and Ψ.
373		THTFU	volts		
374		PSIFU	volts		
375		XMCC1	1/sec	BSETUP	Coefficients of angular momentum of rotating machinery used to compute angular accelerations. Definitions are contained in Appendix A.
376		XMCC2	1/sec		
377		XMCC3	1/sec		
378		XMCC4	1/sec		
379		XMCC5	1/sec		
380		XMCC6	1/sec		
381		XMCC7	1/sec		
382		EOMX	slug-ft^2/sec	0.	Body axis components of angular momentum due to rotating machinery.
383		EOMY	slug-ft^2/sec	0.	
384		EOMZ	slug-ft^2/sec	0.	
385		PBDPL	rad/sec^2	0.	Angular accelerations input to the BMOTION subroutine when the flexible aircraft option is on (IFLEX=1). They are not integrated.
386		QBDPL	rad/sec^2	0.	
387		RBDPL	rad/sec^2	0.	
388		DPPHI	rad	0.	Perturbation Euler angles added to the Redifon servo commands computed in the BVISUAL subroutine (used to simulate body bending).
389		DFTHT	rad	0.	
390		DFPSI	rad	0.	
391	$\dot{p}'_B$	STATE1	rad/sec^2	BQUIET	Intermediate variables used by the trim subroutine, BQUIET.
392	$\dot{q}'_B$	STATE2	rad/sec^2		
393	$\dot{r}'_B$	STATE3	rad/sec^2		
394	$\dot{u}'_B$	STATE4	ft/sec^2		
395	$\dot{v}'_B$	STATE5	ft/sec^2		
396	$\dot{w}'_B$	STATE6	ft/sec^2		
397		CTRIM1	-		Controls used to trim the aircraft. The trim subroutine, BQUIET, systematically varies these variables until the linear and angular accelerations meet certain error criteria.
398		CTRIM2	-		
399		CTRIM3	-		
400		CTRIM4	-		
401		CTRIM5	-		
402		CTRIM6	-		

COMMON NUMBER	VARIABLE	FORTRAN NAME	UNITS	ORIGIN AND/OR DEFAULT VALUE	DESCRIPTION
403		PSIRED	volts	BVISUAL	Course and fine heading command signals used by the Redifon servos.
404		PSIBLK	volts		
405		DTUSED	sec	SMAIN	Frame time of ADC/DAC serving.
406		UBIC	ft/sec	0.	Body axis components of the initial aircraft velocity wrt the wind. Used to specify the initial aircraft velocity if the switch IMACH = -1.
407		VBIC	ft/sec	0.	
408		WBIC	ft/sec	0.	
409		RESTR1	ND	-	Two words used to specify the name of the realtime overlay (EBCDIC).
410		RESTR2	ND	-	
411	L_v	VAL	ft	WINDC	Scale length used by the turbulence model.
412	σ_v	VDISP	ft/sec	WINDC	RMS level of the v component of turbulence.
413		UBD	ft/sec^2	BALFBET	Body axis components of the aircraft acceleration wrt the air mass.
414		VBD	ft/sec^2		
415		WBD	ft/sec^2		
416		VTWN	ft/sec	BVELOCIT	Local axis components of the wind plus random gusts (atmospheric turbulence).
417		VTWE	ft/sec		
418		VTWD	ft/sec		
419		VNTURB	ft/sec		Local axis components of the random gusts (atmospheric turbulence).
420		VETURB	ft/sec		
421		VDTURB	ft/sec		
422		ZERO	ND	0.	This variable is assigned to all unused DAC's.
423		ACYCLE	ND	BVISUAL	Floating point representation of ICYCLE.
424	P/P_o	PAMBR	ND	BATMOSPH	Ratio of ambient to sea level pressure.
425	T/T_o	TAMBR	ND		Ratio of ambient to sea level temperature.
426	tan λ	TLAT	ND	BEARTH	Tangent of the aircraft's latitude.

TABLE B-2

LIST AND DESCRIPTION OF BASIC FIXED POINT COMMON, IFIXED

COMMON NUMBER	FORTRAN NAME	ORIGIN AND/OR DEFAULT VALUE	DESCRIPTION
1	IMODE	MOTHER	Mode control integer.
2	INGT	BLGA	Nose gear on ground*.
3	IRGT		Right main gear on ground*.
4	ILGT		Left main gear on ground*.
5	ISTRIK		Tail on ground*.
6	IFLAT	0	Flat earth option*.
7	IFFCI	0	Fixed-flight de-bug in progress.
8	ISINW	BDCHEK5	Sine wave input.
9	IHIT	BLGA	Ground touched by wheel or tail*.
10	IWEEL	INS10B	Landing gear down*.
11	IWEELC	0	Command landing gear down*.
12	ILGTRN	INS10B	Landing gear in transit*.
13	IOM		Over outer marker*.
14	IMM		Over middle marker*.
15	IAIR		Airways busy*.
16	IFLARE		Below flare height*.
17	I200		Below 200 feet*.
18	I1500		Below 1500 feet*.
19	IBURN	ENGINE	Confirm afterburning occurring*.
20	ISHAKE	0	Shake stick, stall*.
21	IEVAL	BQUIET	Primary trim evaluation flip-flop.
22	ICYCLE	INS10B	Cycling computer off-line indicator
23	ITPROG	BQUIET	Satisfactory trim progress.
24	IFROM	0	Aircraft moving away from beacon.
25	IMDA	INS10B	Altitude trip pilot light, pilot selective.

* Variable = 1 for condition indicated; otherwise zero.

COMMON NUMBER	FORTRAN NAME	ORIGIN AND/OR DEFAULT VALUE	DESCRIPTION
26	IMD1	- - -	Used by EAI 8400 only.
27	IMD2	- - -	Used by EAI 8400 only.
28	IMD3	- - -	Used by EAI 8400 only.
29	IAND	DI, 0	Trim tab, nose down*.
30	IANU		Trim tab, nose up*.
31	IANL		Trim tab, nose left*.
32	IANR		Trim tab, nose right*.
33	ILWD		Trim tab, left wing down*.
34	IRWD		Trim tab, right wing down*.
35	IEBURN		Enable afterburners*.
36	IPDAMP		Activate roll dampers*.
37	IQDAMP		Activate pitch dampers*.
38	IRDAMP		Activate yaw dampers*.
39	IREC1		Reverse thrust discrete, engine 1*.
40	IREC2		Reverse thrust discrete, engine 2*.
41	IREC3		Reverse thrust discrete, engine 3*.
42	IREC4		Reverse thrust discrete, engine 4*.
43	IEGAG1		Command autothrottle activation*.
44	IEGAG2		Select mach hold mode*.
45	IEGAG3		Select IAS hold mode*.
46	IEGAG4		Select IAS select mode*.
47	IAUT1		Skew rate, forward slow*.
48	IAUT2		Skew rate, forward fast*.
49	IAUT3		Skew rate, aft slow*.
50	IAUT4		Skew rate, aft fast*.
51	IABRAK		Activate air brakes*.
52	IPARAC		Activate parachute*.
53	IVISRE		Lower visre*.

* Variable = 1 for condition indicated; otherwise zero.

COMMON NUMBER	FORTRAN NAME	ORIGIN AND/OR DEFAULT VALUE	DESCRIPTION
54	ICAB	DI, 0	Activate HSCAL device*.
55	NLONG	5	Long side count, strip chart DAC multiplexing.
56	NSHORT	2	Short side count, strip chart DAC multiplexing.
57	IFAIL1	DI, 0	Failure of Engine No. 1.
58	IFAIL2		Failure of Engine No. 2.
59	IFAIL3		Failure of Engine No. 3.
60	IFAIL4	↓	Failure of Engine No. 4.
61	IDT1	22	Fastest loop time in milliseconds.
62	IDT2	SMAIN, 44	2nd fastest loop time in milliseconds.
63	IDT3	SMAIN, 88	3rd fastest loop time in milliseconds.
64	ICG	0	Input positions are c.g. relative to runway*.
65	ID	SMAIN	MOTHER initialization integer.
66	IMREQ	-1	Requested mode.
67	IMCAB	0	Mode control in the cab*.
68	IMSECS	1	Mode control at the SECS station*.
69	IMHIS	1	Mode control through the HIS rack*.
70	NDI	128	Number of input discretes.
71	NDO	192	Number of output discretes.
72	NAD	64	Number of ADC's.
73	NDA	128	Number of DAC's.
74	INDEXT	0	Coded trim select.
75	NOLAG	0	Coded quantity under trim control.
76	IABOVE	INS10B	Above obstacle plane*.
77	IBELOW	INS10B	Below obstacle plane*.
78	IDYNCH	0	Dynamic check request.
79	NS1	SPEEDC	
80	NS2		Used for strip chart speed control.
81	NS3		
82	NS4	↓	

* Variable = 1 for condition indicated; otherwise zero.

COMMON NUMBER	FORTRAN NAME	ORIGIN AND/OR DEFAULT VALUE	DESCRIPTION
83	ISHOW	0	Takeoff or landing printout enable*.
84	INUMBER	0	Numbering option enabled*.
85	ITASYL	INS10B	Thrust assymetry, yaw left*.
86	ITASYR	INS10B	Thrust assymetry, yaw right*.
87	INALG1	- - -	
88	INALG2	- - -	Not used.
89	INALG3	- - -	
90	ICH1	- - -	
91	ICH2	- - -	
92	ICH3	- - -	
93	ICH4	- - -	
94	ICH5	- - -	
95	ICH6	- - -	Reserved for any special purpose switches.
96	ICH7	- - -	
97	ICH8	- - -	
98	ICH9	- - -	
99	ICH10	- - -	
100	ICH11	- - -	
101	ICH12	- - -	
102	ITRIM	BQUIET, 0	Aircraft is trimming*.
103	ITRMP	BQUIET	Past value of ITRMCM.
104	IPRINT	0	Enable printout routine*.
105	NRUN	SLOOP1	Run number.
106	IRE1	ENGINE	Engine 1 reversing*.
107	IRE2		Engine 2 reversing*.
108	IRE3		Engine 3 reversing*.
109	IRE4		Engine 4 reversing*.
110	ICHART	INS10B	Strip chart recorders on*.
111	ITRMCM	0	Initiate the trim program*.

* Variable = 1 for condition indicated; otherwise zero.

COMMON NUMBER	FORTRAN NAME	ORIGIN AND/OR DEFAULT VALUE	DESCRIPTION
112	IYBEND	0	Enable Y bending mode*.
113	IZBEND	0	Enable Z bending mode*.
114	IMACH	0	Initial velocity condition is coded†.
115	IFULLV	0	Not used.
116	IFOGIT	BVISUAL	Socked in discrete*.
117	IDUMFU	0	Dummy motion follow-ups enabled*.
118	ICODE	17	Coded dynamic check sequence, see BDCHK5.
119	IGAMTM	0	Trim mode, when enabled, is on gamma.
120	IDISIE	1	Enable input discretes*.
121	IDISOE	1	Enable output discretes*.
122	IASFLP	INS10B	IAS flip-flop.
123	ISITR	0	Right hand controls in command*.
124	ICPRNT	0	Print initial conditions*.
125	IRUMBL	0	Enable runway rumble*.
126	IRUND	0	RUNDUM enable*.
127	IGS2	INS10B	Inside middle marker event*.
128	IEVENT	DI, 0	Pilot event*.
129	ILGUP	INS10B	Landing gear up*.
130	IEFAIL	INS10B	At least one engine failed*.
131	NCOPY	1	Number of print copies requested.
132	IPSIDR	INS10A	Heading instrument drive discrete (see PSIDR).
133	IPEN1	DO, 0	X-Y plotter pen down command, Recorder 1*.
134	IPEN2		X-Y plotter pen down command, Recorder 2*.
135	IPEN3		X-Y plotter pen down command, Recorder 3*.
136	NEWNZE	0	Option for non-repeatable turbulence*.
137	ITUB	- - -	Not used.

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* Variable = 1 for condition indicated; otherwise zero.

† If IMACH =
$\begin{cases} 1 & \text{use VEQIC as initial Mach number} \\ 0 & \text{use VEQIC as initial equivalent airspeed} \\ -1 & \text{use UBIC, VBIC, and WBIC as initial velocity components relative to air mass} \end{cases}$

COMMON NUMBER	FORTRAN NAME	ORIGIN AND/OR DEFAULT VALUE	DESCRIPTION
138	IRUNS1	- - -	
139	IRUNS2	- - -	Not used.
140	IRUNS3	- - -	
141	ICOND	0	Constant density selection switch (see HRHOZ)*.
142	NEWTPE	BRUNDM	Label new RUNDUM tape switch*.
143	ISTACK	BRUNDM	Stack RUNDUM files option*.
144	NRDDT	1	Multiples of frame time for RUNDUM data taking.
145	NLIST	0	No. of variables to be recorded by RUNDUM.
146	IZZSWP	- - -	
147	IONCE	- - -	Used by EAI 8400 only.
148	IBOPT	- - -	
149	IAUTO	USER	Commands auto hold when set.
150	ICRG0	- - -	
151	ICRG1	- - -	
152	ICRG3	- - -	
153	ICRG4	- - -	
154	ICRG7	- - -	
155	ICRG8	- - -	Console registers used by EAI 8400.
156	ICRG9	- - -	
157	ICRG10	- - -	
158	ICRG11	- - -	
159	ICRG13	- - -	
160	ICRG14	- - -	
161	ICRG15	- - -	
162	IVFA	1	Select visual system.
163	IFLEX	0	Enable motion flex computations*.
164	N2	2	Loop 2 multiple of loop 1 (see IDT1).
165	N3	4	Loop 3 multiple of loop 1 (see IDT1).
166	ITBAD	BQUIET	Control limit interference during trim.
167	IM	BQUIET	Control increment flag for BQUIET.

* Variable = 1 for condition indicated; otherwise zero.

COMMON NUMBER	FORTRAN NAME	ORIGIN AND/OR DEFAULT VALUE	DESCRIPTION
168	MODENB	BMOTION	Motion operator mode control.
169	ICENAB	BMOTION	Command to enable motion drive racks.
170	IDTFST	MOTHER	Fast I.C. frame time (msecs).
171	NHOLD	10	No. of hold cycle interations.
172	NADIN	SDAC	Enable ADC's*.
173	ISHORT	SDAC	Enable short side output*.
174	ILONG	SDAC	Enable long side output*.
175	IDRENB	DI	Motion drive racks enabled*.
176	INSDAC	DATA	Enable instrument DAC's*.
177	LOOPDR	DI	Drive rack loops are closed*.
178	ICDATC	INS10B	IC data outputs are still active*.
179	IREVAL	- - -	Not used.
180	NUSED	2	Ratio of ADC/DAC frame time to loop 1 frame time.
181	IDASTR	0	Starting channel number for ADC/DAC conversion.
182	ISTAB	0	Enable stability derivative evaluation*.
183	IVISFU	- - -	Note used.
184	IEULR	0	Interpret IC angular rates as Euler angle rates*.
185	IETURB	0	Turbulence is in local axes instead of body axes*.
186	IGRCMP	0	Turbulence continues after landing gear hits*.
187	ITOMTR	0	Zero $\dot{\alpha}$ and β in I.C.
188	IBTRAN	BTRANSFO and BLGA	Flag indicating updated axis transformation matrix.

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* Variable = 1 for condition indicated, otherwise zero.

APPENDIX C

MOTION DRIVE LOGIC MNEMONICS AND DEFAULT VALUES

This appendix contains Table C-1 which lists all the motion system drive logic mnemonics and default values.

TABLE C-1

MOTION DRIVE LOGIC MNEMONICS AND DEFAULT VALUES

BLOCK DIAGRAM SYMBOL	FORTRAN NAME	DEFAULT VALUE	UNITS
	GAINS		
K_{X_1}	AK1X	1.0	-
K_{X_2}	AK5X	2.0	sec^{-1}
K_{X_3}	AKR1X	1.0	-
K_X	AKXN	0	-
K_{Y_1}	AK1Y	1.0	-
K_{Y_2}	AK5Y	0.1	sec^{-1}
K_{Y_3}	AKR1Y	1.0	-
K_Y	AKYN	1.0	-
K_{Z_1}	AK1Z	1.0	-
K_{Z_2}	AK5Z	1.0	sec^{-1}
K_{φ_1}	AK1P	1.0	-
K_{φ_2}	AK5P	1.0	sec^{-1}
K_P	AKPL	4.0	rad/sec
K_{PQ}	AKPQ	1.0	ft/sec
K_{θ_1}	AK1Q	1.0	-
K_{θ_2}	AK5Q	1.0	sec^{-1}
K_Q	AKQL	0.25	rad/sec
K_{ψ_1}	AK1R	1.0	-
K_{ψ_2}	AK5R	1.0	sec^{-1}

TABLE C-1 (Continued)

BLOCK DIAGRAM SYMBOL	FORTRAN NAME	DEFAULT VALUE	UNITS
		FILTER PARAMETERS	
ω_{AX}	AØMEGX	0.4	rad/sec
ω_{AY}	AØMEGY	0.25	rad/sec
ω_{AZ}	AØMEGZ	0.4	rad/sec
$\omega_{A\varphi}$	AØMEGP	0.25	rad/sec
$\omega_{A\theta}$	AØMEGQ	0.25	rad/sec
$\omega_{A\psi}$	AØMEGR	0.25	rad/sec
ζ_{AZ}	AZETAX	1.4	-
ζ_{AY}	AZETAY	1.4	-
ζ_{AZ}	AZETAZ	1.4	-
$\zeta_{A\varphi}$	AZETAP	1.4	-
$\zeta_{A\theta}$	AZETAQ	1.4	-
$\zeta_{A\psi}$	AZETAR	1.4	-
ω_{BX}	AØMGBX	0.4	rad/sec
ω_{BY}	AØMGBY	0.25	rad/sec
ω_{BZ}	AØMGBZ	0.4	rad/sec
$\omega_{B\varphi}$	AØMGBP	0.25	rad/sec
$\omega_{B\theta}$	AØMGBQ	0.25	rad/sec
$\omega_{B\psi}$	AØMGBR	0.25	rad/sec
ζ_{BX}	AZETBX	1.4	-
ζ_{BY}	AZETBY	1.4	-
ζ_{BZ}	AZETBZ	1.4	-

TABLE C-1   (Continued)

BLOCK DIAGRAM SYMBOL	FORTRAN NAME	DEFAULT VALUE	UNITS
$\zeta_{B\varphi}$	AZETBP	1.4	-
$\zeta_{B\theta}$	AZETBQ	1.4	-
$\zeta_{B\psi}$	AZETBR	1.4	-
ω_{CX}	AØMGCX	0.18	rad/sec
ω_{CY}	AØMGCY	0.75	rad/sec
ζ_{CX}	AZETCX	1.0	-
ζ_{CY}	AZETCY	1.0	-
ω_{DX}	AØMGDX	0.18	rad/sec
ω_{DY}	AØMGDY	0.75	rad/sec
ζ_{DX}	AZETDX	1.0	-
ζ_{DY}	AZETDY	1.0	-
τ_{AX}	TAUF(1)	20.	sec
τ_{AY}	TAUF(2)	20.	sec
τ_{AZ}	TAUF(3)	30.	sec
$\tau_{A\varphi}$	TAUF(4)	20.	sec
$\tau_{A\theta}$	TAUF(5)	20.	sec
$\tau_{A\psi}$	TAUF(6)	20.	sec
τ_{BX}	TAUF(7)	10.	sec
τ_{BY}	TAUF(8)	10.	sec
LIMITER PARAMETERS			
	AMA(1)	2.8	ft
	AMA(2)	37.0	ft

TABLE C-1   (Concluded)

BLOCK DIAGRAM SYMBOL	FORTRAN NAME	DEFAULT VALUE	UNITS
	AMA(3)	3.9	ft
	AMA(4)	0.6283	rad
	AMA(5)	0.3141	rad
	AMA(6)	0.4189	rad
	ADMA(1)	5.05	ft/sec
	ADMA(2)	16.0	ft/sec
	ADMA(3)	6.9	ft/sec
	ADMA(4)	0.5	rad/sec
	ADMA(5)	0.5	rad/sec
	ADMA(6)	0.5	rad/sec
	ADDMA(1)	8.0	ft/sec^2
	ADDMA(2)	9.0	ft/sec^2
	ADDMA(3)	11.0	ft/sec^2
	ADDMA(4)	3.2	rad/sec^2
	ADDMA(5)	1.6	rad/sec^2
	ADDMA(6)	1.6	rad/sec^2
	CØNSTK(1)	-1.804	sec^{-1}
	CØNSTK(2)	-0.6	sec^{-1}
	CØNSTK(3)	-1.77	sec^{-1}
	CØNSTK(4)	-2.0	sec^{-1}
	CØNSTK(5)	-2.8	sec^{-1}
	CØNSTK(6)	-2.8	sec^{-1}
	MISCELLANEOUS		
	SCLIM	0.5	-
	I2ND	0	-
	ISEP	0	-

APPENDIX D

MOTION DRIVE LOGIC TRANSFER FUNCTIONS

This appendix contains Figures D-1 and D-2 which show the motion system drive logic transfer functions for the travels used and the recovered motion parameters.

Drive Logic Transfer Functions for Travels Used

$$\frac{X_{SIM}}{A_{X_P}}(s) = G_X(s)\left\{\frac{K_{X_1}s^2}{[\zeta_{AX},\omega_{AX}][\zeta_{BX},\omega_{BX}]}\right\}\left\{\frac{s\left[\frac{1}{\tau_{AX}} + K_{X_2}\right]}{\left[\frac{1}{\tau_{AX}}\right]\left[K_{X_2}G_X(s)\right]}\right\}$$

$$\frac{\theta_{SIM}}{A_{X_P}}(s) = \frac{G_\theta(s)}{g}\left\{\frac{K_{X_3}[\zeta_{AX},\omega_{AX}][\zeta_{BX},\omega_{BX}] - K_{X_1}s^4}{[\zeta_{AX},\omega_{AX}][\zeta_{BX},\omega_{BX}]}\right\}\left\{\frac{K_Q}{[K_Q]}\right\}\left\{\frac{\left[K_{\theta_2}\right]}{\left[K_{\theta_2}G_\theta(s)\right]}\right\}$$

$$\frac{X_{SIM}}{\dot{q}_B}(s) = G_X(s)\left\{\frac{-gK_{\theta_1}K_{X_1}s^2}{[\zeta_{A\theta},\omega_{A\theta}][\zeta_{B\theta},\omega_{B\theta}]\left[\frac{1}{\tau_{A\theta}}\right]\left[\frac{1}{\tau_{B\theta}}\right]}\right\}\left\{\frac{s\left[\frac{1}{\tau_{AX}} + K_{X_2}\right]}{\left[\frac{1}{\tau_{AX}}\right]\left[K_{X_2}G_X(s)\right]}\right\}$$

$$\frac{\theta_{SIM}}{\dot{q}_B}(s) = G_\theta(s)\left\{\frac{K_{\theta_1}s^2}{[\zeta_{A\theta},\omega_{A\theta}][\zeta_{B\theta},\omega_{B\theta}]}\right\}\left\{\frac{s\left[\frac{1}{\tau_{A\theta}} + K_{\theta_2}\right]}{\left[\frac{1}{\tau_{A\theta}}\right]\left[K_{\theta_2}G_\theta(s)\right]}\right\}$$

$$\frac{Y_{SIM}}{A_{Y_P}}(s) = G_Y(s)\left\{\frac{K_{Y_1}s^2}{[\zeta_{AY},\omega_{AY}][\zeta_{BY},\omega_{BY}]}\right\}\left\{\frac{s\left[\frac{1}{\tau_{AY}} + K_{Y_2}\right]}{\left[\frac{1}{\tau_{AY}}\right]\left[K_{Y_2}G_Y(s)\right]}\right\}$$

$$\frac{\varphi_{SIM}}{A_{Y_P}}(s) = \frac{-G_\varphi(s)}{g}\left\{\frac{K_{Y_3}[\zeta_{AY},\omega_{AY}][\zeta_{BY},\omega_{BY}] - K_{Y_1}s^4}{[\zeta_{AY},\omega_{AY}][\zeta_{BY},\omega_{BY}]}\right\}\left\{\frac{K_P}{[K_P]}\right\}\left\{\frac{\left[K_{\varphi_2}\right]}{\left[K_{\varphi_2}G_\varphi(s)\right]}\right\}$$

$$\frac{Y_{SIM}}{\dot{p}_B}(s) = G_Y(s) \left\{ \frac{gK_{\varphi_1}K_Y s^2}{[\zeta_{A\varphi},\omega_{A\varphi}][\zeta_{B\varphi},\omega_{B\varphi}]\left[\frac{1}{\tau_{A\varphi}}\right]\left[\frac{1}{\tau_{B\varphi}}\right]} \right\} \left\{ \frac{s\left[\frac{1}{\tau_{AY}} + K_{Y_2}\right]}{\left[\frac{1}{\tau_{AY}}\right]\left[K_{Y_2}G_Y(s)\right]} \right\}$$

$$\frac{\varphi_{SIM}}{\dot{p}_B}(s) = G_\varphi(s) \left\{ \frac{K_{\varphi_1} s^2}{[\zeta_{A\varphi},\omega_{A\varphi}][\zeta_{B\varphi},\omega_{B\varphi}]} \right\} \left\{ \frac{s\left[\frac{1}{\tau_{A\varphi}} + K_{\varphi_2}\right]}{\left[\frac{1}{\tau_{A\varphi}}\right]\left[K_{\varphi_2}G_\varphi(s)\right]} \right\}$$

$$\frac{Z_{SIM}}{A_{Z_P}}(s) = G_Z(s) \left\{ \frac{K_{Z_1} s^2}{[\zeta_{AZ},\omega_{AZ}][\zeta_{BZ},\omega_{BZ}]} \right\} \left\{ \frac{s\left[\frac{1}{\tau_{AZ}} + K_{Z_2}\right]}{\left[\frac{1}{\tau_{AZ}}\right]\left[K_{Z_2}G_Z(s)\right]} \right\}$$

$$\frac{\psi_{SIM}}{\dot{r}_B}(s) = G_\psi(s) \left\{ \frac{K_{\psi_1} s^2}{[\zeta_{A\psi},\omega_{A\psi}][\zeta_{B\psi},\omega_{B\psi}]} \right\} \left\{ \frac{s\left[\frac{1}{\tau_{A\psi}} + K_{\psi_2}\right]}{\left[\frac{1}{\tau_{A\psi}}\right]\left[K_{\psi_2}G_\psi(s)\right]} \right\}$$

NOTES:

1. Abbreviated notation

[a] means $s + a$

$[\zeta,\omega]$ means $s^2 + 2\zeta\omega s + \omega^2$

2. $\dfrac{\theta_{SIM}}{A_{X_P}}$ and $\dfrac{\varphi_{SIM}}{A_{Y_P}}$ are for nominal residual tilt option (IALTRS=1, Figure 5.2.2-1)

D-3

Drive Logic Transfer Function for Recovered Motion Parameters

$$\frac{A_{X_{SIM}}}{A_{X_P}}(s) = s^2 \frac{X_{SIM}}{A_{X_P}}(s) + g\frac{\theta_{SIM}}{A_{X_P}}(s)$$

$$\frac{A_{Y_{SIM}}}{A_{Y_P}}(s) = s^2 \frac{Y_{SIM}}{A_{Y_P}}(s) - g\frac{\varphi_{SIM}}{A_{Y_P}}(s)$$

$$\frac{A_{Z_{SIM}}}{A_{Z_P}}(s) = G_Z(s)\left\{\frac{K_{Z_1}s^4}{[\zeta_{AZ},\omega_{AZ}][\zeta_{BZ},\omega_{BZ}]}\right\}\left\{\frac{s\left[\frac{1}{\tau_{AZ}} + K_{Z_2}\right]}{\left[G_Z(s)K_{Z_2}\right]\left[\frac{1}{\tau_{AZ}}\right]}\right\}$$

$$\frac{\dot{p}_{SIM}}{\dot{p}_B}(s) = G_\varphi(s)\left\{\frac{K_{\varphi_1}s^4}{[\zeta_{A\varphi},\omega_{A\varphi}][\zeta_{B\varphi},\omega_{B\varphi}]}\right\}\left\{\frac{s\left[\frac{1}{\tau_{A\varphi}} + K_{\varphi_2}\right]}{\left[G_\varphi(s)K_{\varphi_2}\right]\left[\frac{1}{\tau_{A\varphi}}\right]}\right\}$$

$$\frac{\dot{q}_{SIM}}{\dot{q}_B}(s) = G_\theta(s)\left\{\frac{K_{\theta_1}s^4}{[\zeta_{A\theta},\omega_{A\theta}][\zeta_{B\theta},\omega_{B\theta}]}\right\}\left\{\frac{s\left[\frac{1}{\tau_{A\theta}} + K_{\theta_2}\right]}{\left[G_\theta(s)K_{\theta_2}\right]\left[\frac{1}{\tau_{A\theta}}\right]}\right\}$$

$$\frac{\dot{r}_{SIM}}{\dot{r}_B}(s) = G_\psi(s)\left\{\frac{K_{\psi_1}s^4}{[\zeta_{A\psi},\omega_{A\psi}][\zeta_{B\psi},\omega_{B\psi}]}\right\}\left\{\frac{s\left[\frac{1}{\tau_{A\psi}} + K_{\psi_2}\right]}{\left[G_\psi(s)K_{\psi_2}\right]\left[\frac{1}{\tau_{A\psi}}\right]}\right\}$$

Figure D-2 (Concluded)

AND:

$$\frac{^{A}X_{SIM}}{\dot{q}_B}(s) = s^2 \frac{X_{SIM}}{\dot{q}_B} + g \frac{\theta_{SIM}}{\dot{q}_B}$$

$$\frac{^{A}Y_{SIM}}{\dot{p}_B}(s) = s^2 \frac{Y_{SIM}}{\dot{p}_B} - g \frac{\varphi_{SIM}}{\dot{p}_B}$$

$$\frac{\dot{q}_{SIM}}{^{A}X_P}(s) = G_\theta(s) \frac{1}{8}\left\{\frac{K_{X_3}[\zeta_{AX},\omega_{AX}][\zeta_{BX},\omega_{BX}] - K_{X_1}s^4}{[\zeta_{AX},\omega_{AX}][\zeta_{BX},\omega_{BX}]}\right\}\left\{\frac{K_Q}{[K_Q]}\right\}\left\{\frac{s\left[K_{\theta_2}\right]}{\left[G_\theta(s)K_{\theta_2}\right]}\right\}$$

$$\frac{\dot{p}_{SIM}}{^{A}Y_P}(s) = G_\varphi(s) - \frac{1}{8}\left\{\frac{K_{Y_3}[\zeta_{AY},\omega_{AY}][\zeta_{BY},\omega_{BY}] - K_{Y_1}s^4}{[\zeta_{AY},\omega_{AY}][\zeta_{BY},\omega_{BY}]}\right\}\left\{\frac{K_P}{[K_P]}\right\}\left\{\frac{s\left[K_{\varphi_2}\right]}{\left[G_\varphi(s)K_{\varphi_2}\right]}\right\}$$