NASA Contractor Report 172352

Interactive Flight Control System Analysis Program

J. K. Mahesh, A. F. Konar, and M. D. Ward

HONEYWELL INC.
Minneapolis, Minnesota 55440

CONTRACT NAS1-16438
June 1984

NASA
National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665

PREFACE

The research described in this report was prepared by Honeywell Inc., Minneapolis, Minnesota 55440, under NASA Langley Research Center Contract No. NAS1-16438. This work was directed by the Vehicle Analysis Branch of the Space Systems Division of the NASA Langley Research Center and was administered by Mr. Richard Powell.

The technical work was conducted by the Research Department at Honeywell's Systems and Research Center. Dr. C.S. Greene was the Honeywell Program Manager, and Dr. J.K. Mahesh was the principal investigator on this contract. Dr. Mahesh was assisted by Dr. A.F. Konar and Mr. M.D. Ward. This report covers work from October 1980 to November 1983.

CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

INTERACTIVE FLIGHT CONTROL SYSTEM ANALYSIS PROGRAM

J.K. Mahesh, A.F. Konar, and M.D. Ward

Honeywell Systems and Research Center

SUMMARY

This is the final report on the interactive flight control system analysis program. It summarizes the development, use, and documentation of the software.

Section 2.0 contains a brief description of the software developed under this program. The modeling, analysis, and synthesis capabilities of the software are also described.

Section 3.0 contains conclusions and recommendations.

1.0 INTRODUCTION

The major objectives of this program were to develop a user-oriented interactive flight control system (FCS) analysis software for Space Transportation System Vehicles (STSV) and to demonstrate the use of this software for the current Space Shuttle and an advanced single-stage-to-orbit (SSTO) vehicle.

The foundation of this new software consists of an existing and well verified flight control analysis program called DIGIKON (ref. 1). A command-based interactive approach was used to modify existing DIGIKON programs for interactive execution on the Control Data Corporation (CDC) Cyber computer. The resulting interactive software is called DIGIKON IV.

Additional modeling programs were developed for interconnecting subsystems using block diagram descriptions and for implementing control systems with mode switches and gain schedules. A nonlinear simulation and linearization capability was developed by modifying an existing Honeywell simulation program.

Additional analysis programs were developed for describing function analyses of nonlinear systems and for frequency response analyses of multi-rate systems. The computational efficiency of the multi-variable root locus programs were improved significantly. A capability was developed where any parameter that defined a FCS could be changed and a root locus computed to enable sensitivity analyses.

Several utility programs were developed for maintaining help files and modeling data. A data base program was developed to store and access various performance data using the CDC random access routines. An on-line editor program was developed based on the CDC XEDIT editor. Some of the capabilities of this on-line editor were developed by the NASA Langley Research Center. Plotting programs were developed using the PLOT10 graphics software for the Tektronix terminals. A batch version of DIGIKON software was developed to solve larger problems.

The Space Shuttle demonstration example was developed by obtaining lateral axis models from Rockwell International under a subcontract and by obtaining the ascent models from Honeywell's Avionics Division. A special capability was developed for the lateral axis Space Shuttle model for performing linear sensitivity analyses. The SSTO demonstration example was generated by the NASA Langley Research Center.

An optimal control synthesis capability was added under a separate contract from the NASA Ames Research Center. This capability was accomplished by modifying KONPACT software (ref. 2) for interactive execution and then integrating it with DIGIKON software. In addition the singular value analysis program was developed for evaluating the robustness property of multi-variable systems.

2.0 INTERACTIVE DIGIKON SOFTWARE DESCRIPTION

Interactive DIGIKON represents an advanced, state-of-the-art tool for modeling and analyzing digital and continuous FCSs. Figure 2.0.1 illustrates an overview of the DIGIKON software system. Interactive DIGIKON uses a command-based approach for interaction between the user and the software. This provides for efficient use of the software by the experienced user, while help commands and prompting by the program for missing parameters provide sufficient assistance to the beginner user. Maintenance of the help files and modeling data is facilitated by means of a random access data base in the utility program. Figure 2.0-2 illustrates the organization of the interactive DIGIKON software. The main executive handles the interaction between the user and the various programs. The various programs, in addition to communicating with the user, communicate directly with the various data files. Descriptions of each of the data files used in the interactive DIGIKON program are given in Table 2.0-1. The user can execute any program by typing in the appropriate command. A list of all of the commands is given in Table 2.0-2.

2.1 State-Space Modeling Capabilities

The modeling programs obtain the standard state-space data from the user-supplied physical description of the linear system. When the system contains nonlinear elements, only the linear part of the system is modeled, and the nonlinear elements are described directly to the particular performance analysis program. In addition to the state-space data, the modeling programs also maintain a "name list data" for the linear systems modeled.

The physical description of the system can take the following forms:

1. Differential or difference equations
2. Continuous or discrete transfer functions
3. Direct state-space data input
4. Interconnection of systems
5. Conditioning of systems
6. Transformation of systems
7. Multi-rate connection of systems

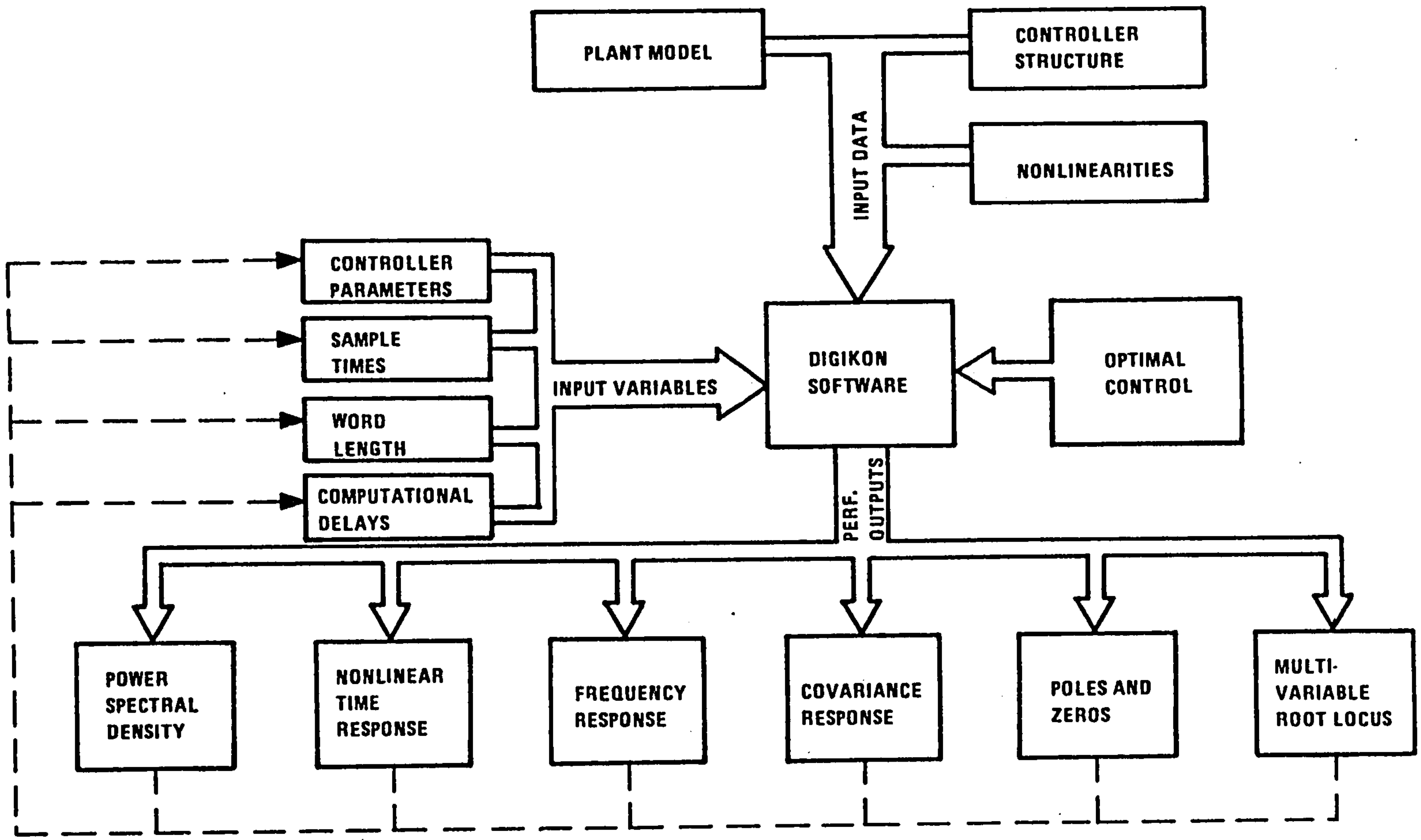

Figure 2.0-1. - DIGIKON software system.

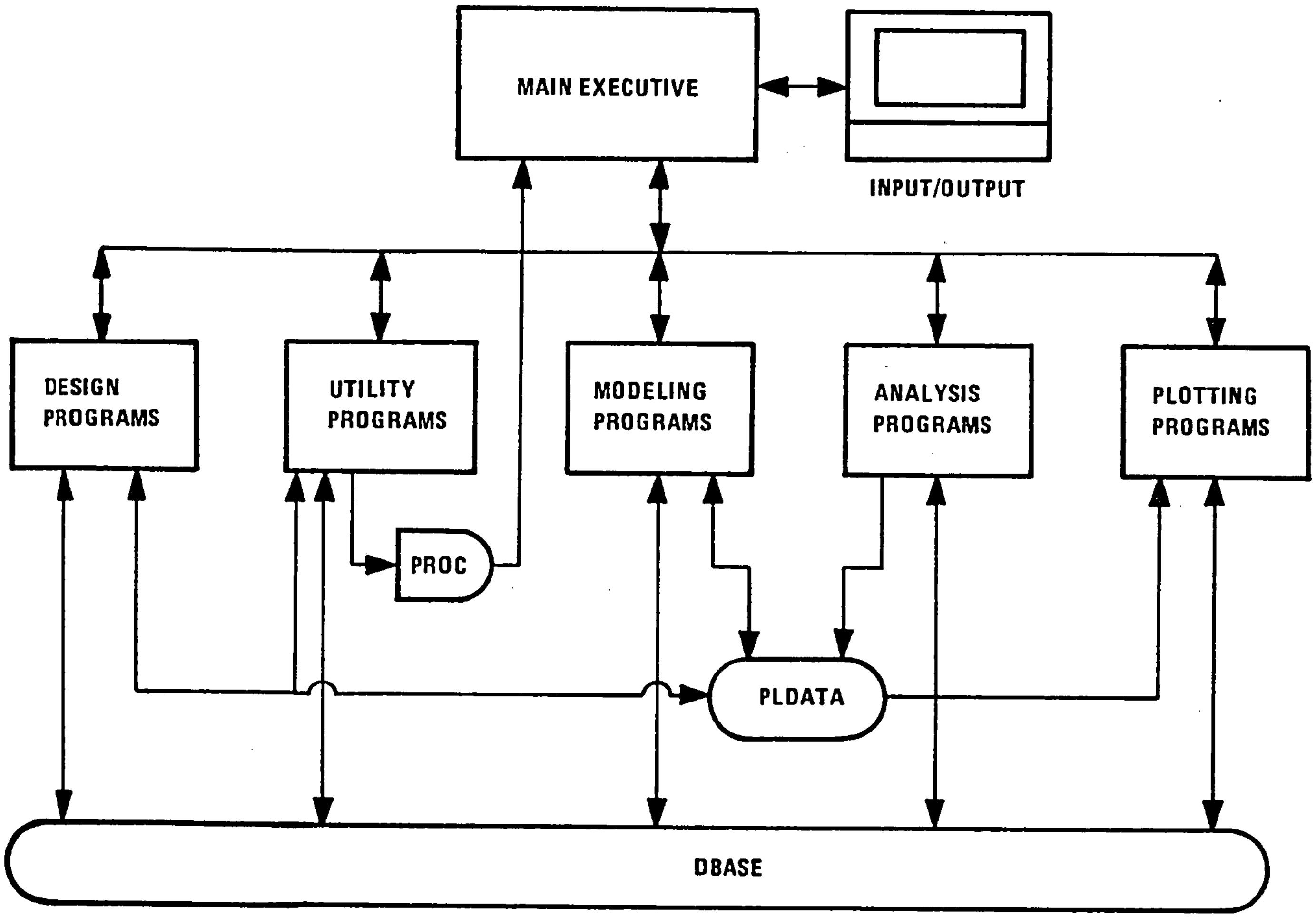

Figure 2.0-2. - Organization of interactive DIGIKON programs.

TABLE 2.0-1. - DESCRIPTION OF DATA FILES USED IN THE INTERACTIVE DIGIKON PROGRAM FOR THE CDC CYBER COMPUTERS

File Name	Code	Description or Contents
INPUT	IR=5	Represents interactive terminal or card reader
OUTPUT	IW=6	Represents interactive terminal or line printer
DBASE	JDB=10	Random access multi-segment file that contains the various help files, user-created modeling data files, system (quadruple and name list) files, root locus plot files, frequency response plot files, and time and covariance response plot files
PROC	JS=2	Contains the user-specified modeling data file for sequential execution by the modeling programs; also used to initially transfer the data base files (help files and modeling data files) from another computer system using the utility program
PLDATA	JP=8	Contains plot data for the plotting program and is also used as a scratch file by various modeling programs

TABLE 2.0-2. - LIST OF INTERACTIVE DIGIKON COMMANDS

Type	Command	Description
Modeling	CDEM	Compute differential equation model
	CTFM	Compute transfer function model
	RQDM	Read quadruple data model
	CQDM	Compute quadruple data model
	CICM	Compute interconnection model
	CBDM	Compute block diagram model
	CCDM	Compute conditioned model
	CZT	Compute Z-transform model
	CTT	Compute Tustin transform model
	CMZT	Compute modified Z-transform model
	CZWT	Compute Z to W transform model
	CWZT	Compute W to Z transform model
	CWLT	Compute word length truncated model
	CVGM	Compute variable gain model
	CCM	Compute controller model
	CQSA	Compute quadruples for sensitivity analysis
	CNSM	Compute nonlinear simulation

TABLE 2.0-2. - CONCLUDED

Type	Command	Description
Analysis	CPZR	Compute pole zero response
	CFR	Compute frequency response
	CNFR	Compute nonlinear frequency response
	CLCA	Compute limit cycle analysis
	CTR	Compute time response
	CNTR	Compute nonlinear time response
	CRL	Compute root locus
	UDRL	Update root locus
	CGRL	Compute generalized root locus
	CNLC	Compute nonlinear covariance response
	CSVD	Compute singular value decomposition
	CPSD	Compute power spectral density
Design	CDNM	Compute design model
	CSFG	Compute state feedback gains
	CKEG	Compute Kalman estimater gains
	CSFS	Compute state feedback system
	COES	Compute optimal estimater system
	COS	Compute optimal system with estimater
	CCOV	Compute covariance analysis
	CCOR	Compute correlation analysis
	RSFG	Reset feedback gains
Plotting	PFR	Plot frequency response
	PTR	Plot time response
	PRL	Plot root locus
	PCR	Plot covariance response
	PSV	Plot singular values
	PSD	Plot power spectral density
Utility	EDIT,FN	Edit data file FN
	PRINT,FN	Print data file FN
	EXEC,FN	Execute data file FN
	HELP,CMD	Help with command CMD
	DELETE,FN	Delete data file FN
	LIST,DT	List data file names of type DT (DT can be PROC or HELP or FREQ or SIMU or ROOT)
	MSREAD	Read from procedure file JS into DBASE
	MSWRITE	Write from DBASE onto procedure file JS
	INIT	Initialize data base
	NAME,SYSN	Print name list data for system SYSN
	QUAD,SYSN	Print quadruple data for system SYSN
	RGPT	Read global plot title
	WGPT	Write global plot title
	FORMAT,OPTN	Define output format (OPTN can be batch or INTERACTIVE or NONE)
	BAUD,N	Change baud rate to N (default value for N is 1200)
	STATUS	Print status of global plot title, format, and baud rate

8. Transfer functions with mode switches and gain schedules
9. Nonlinear system modeling

The differential equation modeling capability is ideally suited to describing equations of motion of aircraft and spacecraft. It can also be conveniently used for any physical process that can be described by either linear differential or difference equations.

The transfer function modeling capability is ideally suited to describing controllers, sensors, actuators, etc. Transfer functions naturally evolve from control system design in the frequency domain. This includes lead-lag filters (used for improving stability), notch filters (used for suppressing unwanted frequency oscillations), etc. In most cases, linear representation of actuators takes the form of transfer functions. Sensors are often represented in the form of transfer functions.

The direct state-space modeling capability can be used to directly input the state-space data of a linear system to the modeling programs. This involves specifying the size of the input, output, and state variables and the elements of either the continuous quadruples (A, B, C, D) or the discrete quadruples (F, G, H, E). It can also be used to input a slightly modified form of standard state-space data in the form of quintuples (F, A, B, C, D).

The interconnection modeling capability is used for combining various subsystems into an overall system. In general, the overall FCS for aircraft or spacecraft consists of various subsystems (actuator, airframe, sensor, controller, etc.). There are two methods for combining subsystems. The first involves the description of the interconnection equations, and the second involves the description of block diagram drawing instructions.

The conditioning modeling capability includes order reduction, by truncation or residualization, and linear transformation to reorder or scale the system variables. Order reduction is useful to get rid of unnecessary dynamics. With linear transformations, the system can be scaled so that the variables conform to a different set of units.

The transformation modeling capability can be used to transform the state-space representation of the linear system between the s, z, and w planes. Discrete models for both the controller and plant are required to perform sample rate and word length tradeoff analyses. The z-transform with zero-order hold is used to develop the discrete model of the plant. The Tustin transform or the regular z-transform can be used to develop the discrete model of the controller. Modified z-transform procedures can be used to introduce time delays. Some direct digital design techniques involve the w-transform of the discrete plant and the controller designed in the w-plane.

The multi-rate modeling capability can be used to model the multi-rate representation of a linear discrete system. Discrete systems are usually structured in multi-rate form due to information-limited sensors, processor-limited controllers, or different bandwidth (BW) of signals (low BW signal should be sampled low, high BW signal should be sampled high due to foldover and roundoff noise). The variable gain method, which is based on time domain decomposition, is used to model multi-rate discrete systems.

Another modeling capability allows modeling of the controller dynamics, consisting of transfer functions with flight-condition-dependent gains and mode switches. This description of the controller can be handled by the transfer function modeling program once the flight condition is fixed. However, it is cumbersome to change the parameters as the flight condition varies. This type of controller description is best modeled by writing a standard FORTRAN subroutine to define the gain schedules, mode switch values, the transfer functions, and their connections.

2.2 Performance Analysis Capabilities

Performance analysis programs use the standard state-space data of the linear system to obtain the specified performance analysis. The various analysis techniques/programs are given below.

- Pole-zero analysis
- Frequency response analysis
- Time response analysis

- Root locus analysis
- Covariance response analysis
- Power spectral-density analysis
- Singular value analysis

Computation of poles of a linear system is essential to determine the stability. The zeros of the transfer function from an input to an output provide valuable information on the system response.

The frequency response method is still the most commonly used classical method for designing and analyzing control systems. The open loop frequency response of a system is computed to determine the margins of stability, the low frequency loop gain, and the high frequency roll-off characteristics. The closed loop frequency response of a system is computed to determine the bandwidth and the bending mode response.

The time response of an FCS to a step input is a frequently used analysis to determine if the system is properly designed. Time response analysis yields information on overshoot, rise time, and settling time of the response variables.

Root locus analysis is one of the commonly used classical methods for designing and analyzing control systems. Multi-variable root locus techniques are used to handle multi-rate digital systems. In addition to providing information about the stability of the control system, root locus techniques can be used to analyze the sensitivity to parameters.

Covariance analysis represents an efficient way of analyzing the performance of systems excited by random inputs. It basically involves the computation of mean and covariance of selected variables as a function of time.

Power spectral-density analysis is used to compute the power content of a signal in a prescribed frequency band to determine significant frequencies of the signal in that band. This, in turn, can be used to indicate how fast the sampling rate should be so that the digital signal is transmitted through the discrete channel without a significant loss of signal power.

Singular value analysis is a new approach to the frequency domain analysis of multi-input/multi-output (MIMO) feedback systems to determine robustness. The robustness of a feedback system is its ability to maintain performance in the face of uncertainties.

A nonlinear simulation capability is used for highly nonlinear FCSs. The ability to simulate nonlinear systems provides a means of determining if the design goals have been achieved. In addition, linearization of the nonlinear simulations provides an important capability.

2.3 Optimal Control Synthesis Capabilities

Optimal control synthesis procedures produce FCS designs that have the following advantages:

- Guaranteed stability
- Computer-automated synthesis
- Integrated multi-variable designs
- Optimal performance

These benefits for an FCS could be interpreted as providing good handling qualities, for example. Integrated multi-variable control design could greatly enhance maneuverability through simultaneous operation of all available control inputs. For integrated vehicle or control-configured vehicle designs, it is necessary to have a computer-aided design capability to conduct rapid design iterations. The optimal control design programs provide the following capabilities:

- Modeling for optimal controller design
- Optimal controller design
  --optimal state feedback gains
  --optimal and robust Kalman estimater gains
- Modeling optimal FCS
- Covariance and correlation analysis

Modeling for optimal controller design involves identification of the input variables as either control-input variables or gust-input variables and identification of the output variables as either performance-output variables or measurement-output variables.

The optimal state feedback design is obtained as a set of state feedback gains. The optimal state feedback control law represents the best that is achievable. It is guaranteed by theory to have good robustness properties.

The estimater design step eliminates the need to have all of the states of the design model. It is assumed that enough sensors are available so that the states of the design model can be estimated. The estimater is obtained as a set of estimater gains. The control law is then obtained by multiplying the estimated states by optimal state feedback gains.

The Kalman estimater gains, along with the state feedback gains, define the optimal estimater system that represents the dynamics of the optimal controller. Once this optimal controller system is obtained, it can be modified to represent suboptimal controller dynamics.

Covariance activity of some of the performance outputs, in particular the control surface activity due to gust and measurement noise, can be evaluated using the covariance program.

2.4 Miscellaneous Capabilities

Various miscellaneous capabilities are available to facilitate efficient use of the DIGIKON software, including:

- Random access data base
- On-line editing
- Multiple plotting
- Batch execution

The data base program maintains a list of help files that can be used to supply information on any specific command. The data base program facilitates storing a sequence of commands and data on a random access file. Once stored, this sequence of commands and data can be executed repeatedly. The data base program stores performance data under different plot file names, which enhances the plotting capability.

The on-line editing capabilities can be used to edit any data base file. This provides a unique capability for the interactive DIGIKON software to readily modify the system description for parametric analysis.

Plotting of performance data is automatic when the interactive DIGIKON software is being executed. Plotting is suppressed when the batch version of the DIGIKON software is being executed. Plotting of stored performance data is easy and flexible. Multiple plotting capability allows plotting of performance data from different cases in a single plot. This capability comes in handy when trying to compare several designs.

The batch version of the DIGIKON software allows larger problems to be solved. The batch DIGIKON software's execution is identical to that of the interactive DIGIKON software. The data base contains all of the performance data generated in batch mode, which can later be plotted using interactive DIGIKON software.

3.0 CONCLUSIONS AND RECOMMENDATIONS

The major objectives of this program were to develop a user-oriented interactive FCS analysis program for STSV and to demonstrate the use of this program for the current Space Shuttle and an advanced SSTO vehicle. The major emphasis has been on the software development and documentation. These objectives were primarily met.

3.1 Significant Results

The work done under this program has defined a very powerful and interactive software for FCS analysis. The chief benefit of the software is to provide integrated software for rapid development of vehicle models and control laws for future applications. The software is called Interactive DIGIKON (DIGIKON IV) and possesses the following capabilities:

- Continuous system modeling with differential equations and transfer functions
- Discrete system modeling including multiple sample rates with transformations (z, modified z, and Tustin) from s-plane to z-plane
- Optimal state feedback, robust Kalman estimater design, and covariance analysis
- Frequency response with Bode, Nichols, and Nyquist plots
- Nonlinear simulation with linearization
- Time response with step, ramp, and sinusoidal inputs and limit-cycle simulation
- Multi-variable root locus and parameter sensitivity analysis
- Describing-function analysis for single nonlinearity
- Random access data base and on-line editor for maintaining flight condition data, FCS models, and macro commands
- Command-oriented interaction with on-line help to provide necessary instruction on the use of commands

3.2 Recommendations for Future Development Work

- Implement MIMO realization for matrix transfer functions
- Develop a capability to input differential/difference equations directly rather than through FORTRAN subroutines
- Develop reduced-order modeling capability using spectral decomposition and residue of the modes
- Develop Monte Carlo simulation capability for analyzing nonlinear systems driven by random inputs
- Develop a capability to compute discrete Fourier transform of time response signals for spectral analysis
- Implement sector stability method for nonlinear system analysis

3.3 Conclusions

A large-scale software for interactive modeling, analyzing, and synthesizing of FCSs has been developed under this program. This software enables engineers to design and verify modern FCSs in a highly efficient manner.

REFERENCES

1. Konar, A.F. and Mahesh, J.K., "Digital Flight Control Systems for Tactical Fighters," Contract No. AFFDL-TR-73-119, Vols. I, II, and III, Honeywell Systems and Research Center, Minneapolis, Minnesota, June 1974.

2. Konar, A.F. and Mahesh, J.K., "Computer Programs for Active Control Technology," Vols. I, II, and III, AFFDL-TR-75-146, Honeywell Systems and Research Center, Minneapolis, Minnesota, August 1976.

1. Report No.
NASA CR-172352

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle

INTERACTIVE FLIGHT CONTROL SYSTEM ANALYSIS PROGRAM

5. Report Date
June 1984

6. Performing Organization Code
41550

7. Author(s)
J.K. Mahesh   M.D. Ward
A.F. Konar

8. Performing Organization Report No.
84SRC10

9. Performing Organization Name and Address
Honeywell Systems and Research Center
2600 Ridgway Parkway, PO Box 312
Minneapolis, Minnesota 55440

10. Work Unit No.

11. Contract or Grant No.
NAS1-16438

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, DC 20546

13. Type of Report and Period Covered
Contractor Report

14. Sponsoring Agency Code
506-63-23-02

15. Supplementary Notes
NASA Langley Technical Monitor, Mr. Richard Powell
Final Report

16. Abstract

A summary of the development, use, and documentation of the interactive software (DIGIKON IV) for flight control system analyses is presented. A list of recommendations for future development is also included.

17. Key Words (Suggested by Author(s))
Flight control system analysis
Interactive design
Digital flight control
Multi-rate analysis

18. Distribution Statement
Unclassified - Unlimited

Subject Category 08

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
21

22. Price*
A02