N90-10090

MODELING AND CONTROL SYSTEM DESIGN AND ANALYSIS TOOLS FOR FLEXIBLE STRUCTURES

By

Amir A. Anissipour
Russell A. Benson
Edward E. Coleman

The Boeing Company
Seattle, Washington

ABSTRACT

Design and analysis of control systems for flexible structures require accurate math models of flexible structures and software design with the analysis tools capable of handling these models while maintaining numerical accuracy. Since aeroelastic models of flexible structures tend to be large (e.g., 100 states), the availability of tools to handle such large models is crucial. Initial model development is based on aerodynamic mathematical models, wind tunnel data, mathematical structural models, and ground shake test results. Eventually, flight test data are used to update and refine the model. This paper describes Boeing software tools used for the development of control laws of flexible structures.

The Boeing Company has developed a software tool called Modern Control Software Package (MPAC). MPAC provides the environment necessary for linear model development, analysis, and controller design for large models of flexible structures. There are two features of MPAC which are particularly appropriate for use with large models: (1) numerical accuracy and (2) label-driven nature. With the first feature MPAC uses double precision arithmetic for all numerical operations and relies on EISPAC and LINPACK for the numerical foundation. With the second feature, all MPAC model inputs, outputs, and states are referenced by user-defined labels. This feature allows model modification while maintaining the same state, input, and output names. In addition, there is no need for the user to keep track of a model variable's matrix row and column locations.

There is a wide range of model manipulation, analysis, and design features within the numerically robust and flexible environment provided by MPAC. Models can be built or modified using either state space or transfer function representations. Existing models can be combined via parallel, series, and feedback connections; and loops of a closed-loop model may be broken for analysis. Analysis tools available include: eigenvalue/eigenvector, controllability matrix, observability matrix, transfer function generation, frequency response and singular value plots, covariance response to white noise or atmospheric turbulence models, model simulation using step, sinusoidal, random, or user-defined inputs. Control system design tools include: root locus, LQG full state feedback gain matrix computation, LQG full-order estimator design, and robust low order controller (SANDY) design as developed by Dr. Uy-Loi Ly at Stanford.

The existing Boeing Company structural analysis and design software package, ATLAS, has been extended in order to form a state-space model for input to MPAC. The new capability, a module named DYFORM, is an outgrowth of earlier work under a NASA contract for Integrated Application of Active Controls. The structural and theoretical aerodynamic mathematical model originates within ATLAS in exactly the same fashion as for conventional flutter and dynamic loads analyses. The DYFORM module is then used to construct the state-variable model as required by MPAC. Its capabilities include (1) control surfaces and/or gust vector as inputs, (2) sensors and/or loads quantities as outputs, (3) formulation in body-fixed or inertial axes, (4) modification of the theoretical aerodynamics using wind tunnel/flight test data from rigid or flexible-model tests, and (5) use of S-plane rational airloads expressions to formulate the state model including augmented states to represent unsteady aerodynamic effects.

MPAC has been used for yaw damper design (including active flexible mode suppression) of the Boeing 767 and 747 airplanes. The flexible structural models of these planes, as large as 100 states, have been handled by MPAC without loss of numerical accuracy.

The Boeing Company plans for the development of a system identification and parameter estimation (SIPE) software tool. The system identification algorithms employ a multiple stepwise regression technique to determine the structure of the system. The parameter estimation algorithms update the current model using maximum likelihood estimation. The SIPE routines will be compatible with MPAC and RF_DATA (a data correction and reformatting program also developed by Boeing). The SIPE routines will be flexible, allowing the user to select gradient methods, integration algorithms, and Riccati solution algorithms. The MPAC compatible model structure slated for the SIPE package will be applicable to any dynamic system. Aerodynamic, aeroelastic, ground effects, and sensor noise modeling will all be possible.

INTRODUCTION TO MPAC:

A Control Law Design Tool Well Suited for Flexible Structure Applications

Edward E. Coleman

The Boeing Company
Boeing Commercial Airplanes
P.O. Box 3707
Seattle, Washington 98124-2207

Tool Requirements for Models of Flexible Structures:

- o Large model capacity (more than 100 states)
- o Efficient user interface for handling large models
- o Numeric robustness
- o Model reduction techniques

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MPAC - Multivariable control design and analysis PACkage

- Programmable "calculator" for synthesis, manipulation, and analysis of continuous and discrete linear dynamic system models

- MPAC supports:
  - Model development
  - Dynamic system analysis
  - Controller synthesis

- MPAC was originally developed as a batch process tool. An interactive interface is currently being developed for MPAC to improve its ease of use and efficiency.

MPAC Features:

Label Driven Model Format:

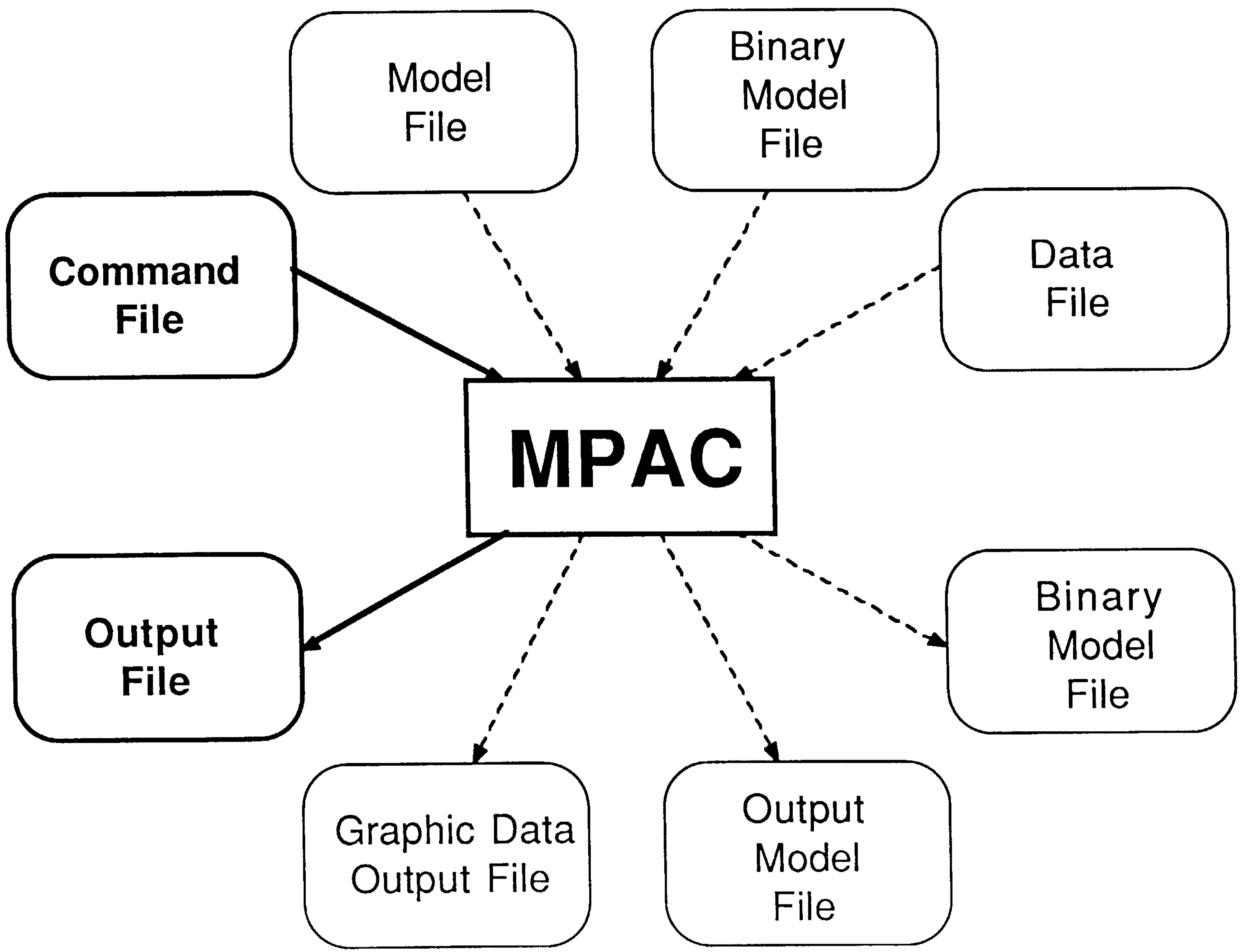
- User defined state, input, and output labels of up to 8 characters.

Numeric Robustness:

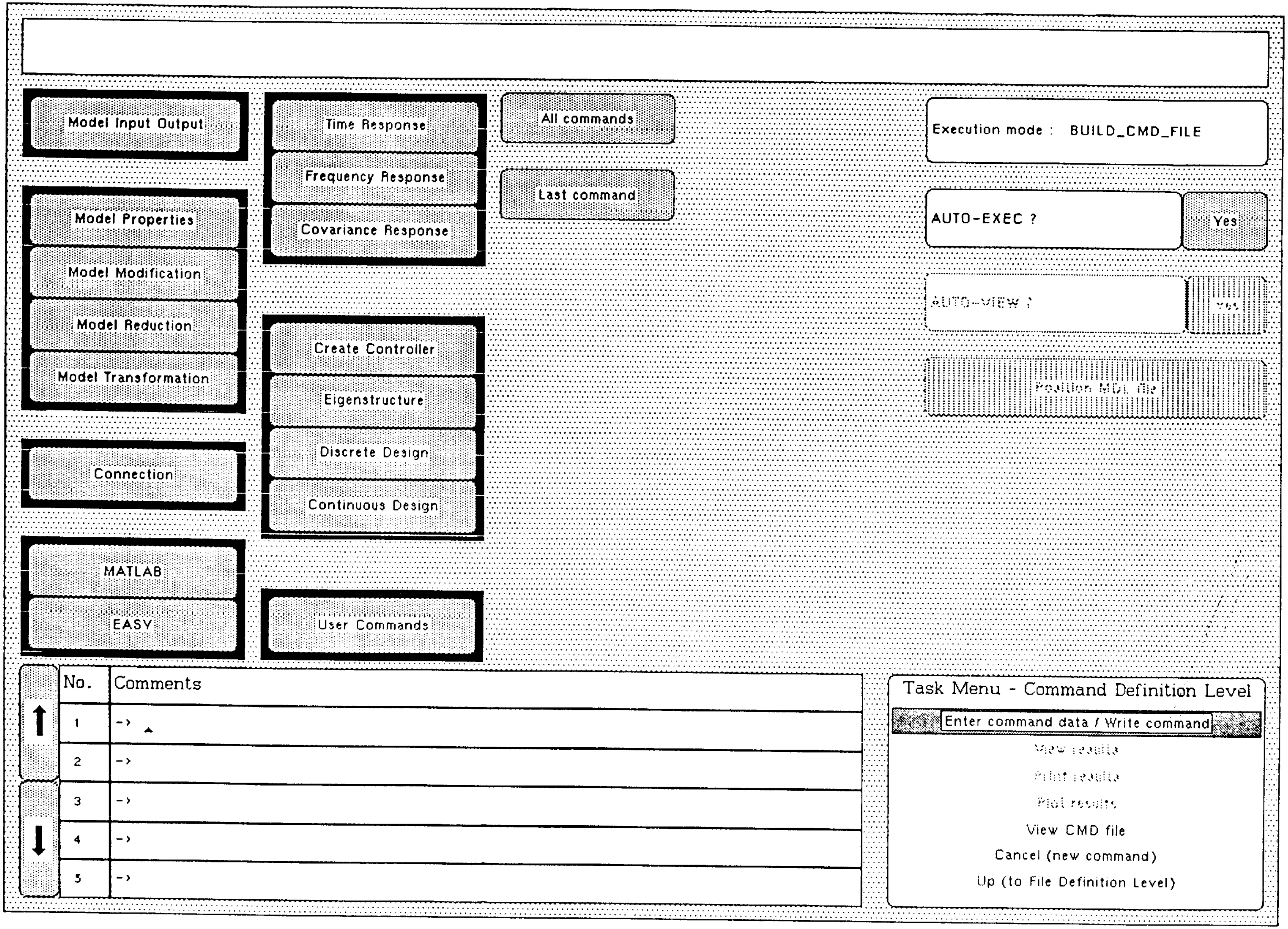
- Built on Eispac, LINPACK, and ORCALS
- Double precission computation throughout
- Handles models up to 256 elements (states, inputs, and outputs)

Modular Structure:

- Each command is a seperate subroutine
- User need learn only those comands he/she wants to use
- Wide range of available commands
- Provission for customized, user defined commands



Model File
Binary Model File
Command File
Data File
MPAC
Output File
Binary Model File
Graphic Data Output File
Output Model File



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Model Input Output

Model Properties

Model Modification

Model Reduction

Model Transformation

Connection

MATLAB

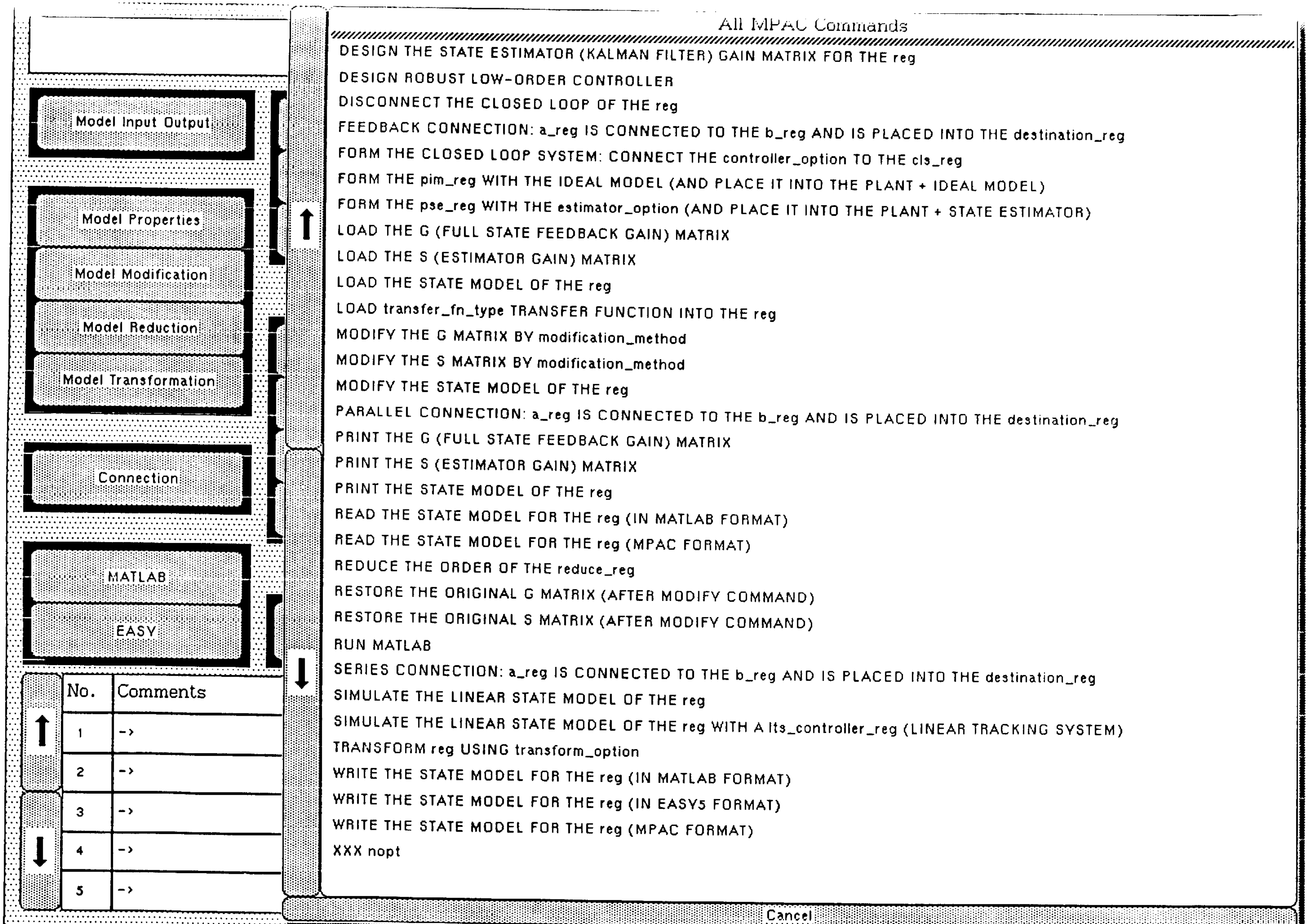
EASY

No.	Comments
1	->
2	->
3	->
4	->
5	->

All MPAC Commands

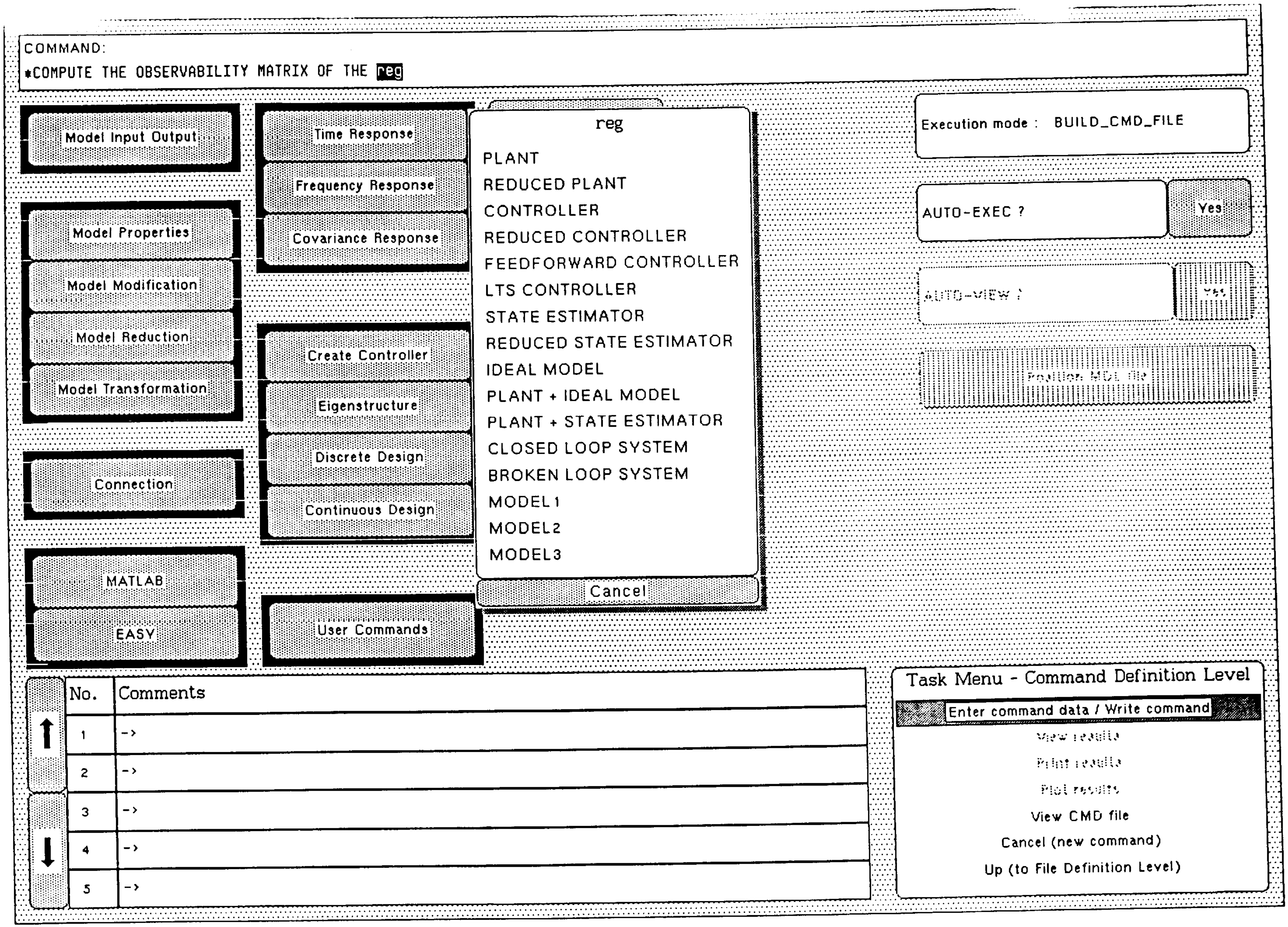
COMPUTE THE ASYMPTOTIC POLES OF FULL STATE FEEDBACK GAIN FOR THE reg
COMPUTE THE ASYMPTOTIC POLES OF KALMAN FILTER GAIN FOR THE reg
COMPUTE THE COMPANION MODAL MODEL OF THE reg, replacement_option
COMPUTE THE CONJUGATE MODAL MODEL OF THE reg, replacement_option
COMPUTE THE CONTROLLABILITY MATRIX OF THE reg
COMPUTE THE COVARIANCE RESPONSE OF THE reg TO turbulence_model AND covariance_print_option
COMPUTE THE COVARIANCE RESPONSE OF THE reg TO WHITE NOISE AND covariance_print_option
COMPUTE THE DISCRETE COVARIANCE RESPONSE OF THE reg TO WHITE NOISE AND covariance_print_option
COMPUTE THE EIGENVALUES OF THE reg
COMPUTE THE EIGENVECTORS OF THE reg
COMPUTE THE FREQUENCY RESPONSE OF THE reg
COMPUTE THE OBSERVABILITY MATRIX OF THE reg
COMPUTE THE RESIDUES OF THE reg
COMPUTE THE ROOT LOCUS OF THE reg
COMPUTE THE SETPOINT MATRICES FOR THE reg
COMPUTE THE SIMILARITY TRANSFORM OF THE STATE MODEL FOR THE reg
COMPUTE THE SINGULAR VALUES OF THE reg
COMPUTE THE TRANSFER FUNCTION(S) OF THE reg
COMPUTE THE TRANSMISSION ZEROS OF THE reg
CONSTRUCT THE DRYDEN TURBULENCE MODEL FOR THE reg
CONSTRUCT THE EQUATIONS OF MOTION FOR THE reg
COPY THE STATE MODEL OF THE reg TO THE destination_reg
CREATE STATE ESTIMATOR FOR THE reg
CREATE controller_type FOR THE reg
CREATE controller_type FOR THE reg WITH MODEL FOLLOWING
DESIGN THE DISCRETE FSF (FULL STATE FEEDBACK) GAIN MATRIX FOR THE reg
DESIGN THE DISCRETE STATE ESTIMATOR (KALMAN FILTER) GAIN MATRIX FOR THE reg
DESIGN THE EMF (EXPLICIT MODEL FOLLOWING) GAIN MATRIX FOR THE reg
DESIGN THE FSF (FULL STATE FEEDBACK) GAIN MATRIX FOR THE reg
DESIGN THE LTS (LINEAR TRACKING SYSTEM) GAIN MATRIX FOR THE reg
DESIGN THE STATE ESTIMATOR (KALMAN FILTER) GAIN MATRIX FOR THE reg
DESIGN ROBUST LOW-ORDER CONTROLLER

Cancel



All MPAC Commands
DESIGN THE STATE ESTIMATOR (KALMAN FILTER) GAIN MATRIX FOR THE reg
DESIGN ROBUST LOW-ORDER CONTROLLER
DISCONNECT THE CLOSED LOOP OF THE reg
FEEDBACK CONNECTION: a_reg IS CONNECTED TO THE b_reg AND IS PLACED INTO THE destination_reg
FORM THE CLOSED LOOP SYSTEM: CONNECT THE controller_option TO THE cls_reg
FORM THE pim_reg WITH THE IDEAL MODEL (AND PLACE IT INTO THE PLANT + IDEAL MODEL)
FORM THE pse_reg WITH THE estimator_option (AND PLACE IT INTO THE PLANT + STATE ESTIMATOR)
LOAD THE G (FULL STATE FEEDBACK GAIN) MATRIX
LOAD THE S (ESTIMATOR GAIN) MATRIX
LOAD THE STATE MODEL OF THE reg
LOAD transfer_fn_type TRANSFER FUNCTION INTO THE reg
MODIFY THE G MATRIX BY modification_method
MODIFY THE S MATRIX BY modification_method
MODIFY THE STATE MODEL OF THE reg
PARALLEL CONNECTION: a_reg IS CONNECTED TO THE b_reg AND IS PLACED INTO THE destination_reg
PRINT THE G (FULL STATE FEEDBACK GAIN) MATRIX
PRINT THE S (ESTIMATOR GAIN) MATRIX
PRINT THE STATE MODEL OF THE reg
READ THE STATE MODEL FOR THE reg (IN MATLAB FORMAT)
READ THE STATE MODEL FOR THE reg (MPAC FORMAT)
REDUCE THE ORDER OF THE reduce_reg
RESTORE THE ORIGINAL G MATRIX (AFTER MODIFY COMMAND)
RESTORE THE ORIGINAL S MATRIX (AFTER MODIFY COMMAND)
RUN MATLAB
SERIES CONNECTION: a_reg IS CONNECTED TO THE b_reg AND IS PLACED INTO THE destination_reg
SIMULATE THE LINEAR STATE MODEL OF THE reg
SIMULATE THE LINEAR STATE MODEL OF THE reg WITH A lts_controller_reg (LINEAR TRACKING SYSTEM)
TRANSFORM reg USING transform_option
WRITE THE STATE MODEL FOR THE reg (IN MATLAB FORMAT)
WRITE THE STATE MODEL FOR THE reg (IN EASY5 FORMAT)
WRITE THE STATE MODEL FOR THE reg (MPAC FORMAT)
XXX nopt
Cancel
Model Input Output
Model Properties
Model Modification
Model Reduction
Model Transformation
Connection
MATLAB
EASY
No.
Comments
1 ->
2 ->
3 ->
4 ->
5 ->

230



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This is an example MPAC command file. The output file generated using this command file is given on the following pages.

```
*MPAC READ PLANT
LAT2.MDL

*COMPUTE EIGENVALUES OF PLANT

*DEFINE PLANT
DELETE STATE  PSI
CREATE STATE BETA_INT.dot:  1. BETA
CREATE OUTPUT PHI_CRIT:    1. PHI.dot   5.0 PHI
CREATE OUTPUT BETA_CRIT:   1. BETA.dot  3.2 BETA  4. BETA_INT
END

*DESIGN GAIN MATRIX FOR PLANT
.001
2, 2
'AIL'          1.
'RUD'          2.
'PHI_CRIT'     4.
'BETA_CRIT'    1.
'WLOCUS'   'RHO'  1.,  1.,  1
$    FIRST CUT LATERAL GAIN LOCUS
$          AIL=1. RUD=2.
$      PHI_CRIT=4. BETA_CRIT=1.

*CREATE CONTROLLER FOR PLANT
'NODIRECT'

*FORM PLANT + CONTROLLER

*PRINT CLOSED-LOOP SYSTEM

*COMPUTE EIGENVALUES OF CLOSED-LOOP SYSTEM

*MPAC WRITE CLOSED-LOOP SYSTEM
CLOSED_LOOP.MDL
```

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MPAC output file example. Output file generated using command file on previous

```
      MPAC RELEASE VERSION 4.00   05 MAY 1987         (CONFIGURATION CONTROL I

*******************************************************
*=====================================================*
*          MPAC INPUT/OUTPUT FILE DESCRIPTION         *
*=====================================================*
*******************************************************

 COMMAND FILE ------------------ example.cmd
 MODEL FILE --------------------
 INPUT BINARY FILE -------------
 OUTPUT BINARY FILE ------------
 MPAC OUTPUT FILE -------------- example.out
 MPAC GGP PLOT FILE ------------ example.ggp
 MPAC USER DATA FILE NO.1 -----
 MPAC USER DATA FILE NO.2 -----
 MPAC USER-DEFINED UBIN FILE --
 TIME OF MPAC JOB EXECUTION --- Tuesday, July 5, 1988   3:50:36 pm (PST)

*******************************************************


*************************************************************************
*************************************************************************
*************************************************************************
******                                                             ******
******  MODERN CONTROL THEORY ANALYSIS/SYNTHESIS SOFTWARE PACKAGE  ******
******                                                             ******
******        APOLLO-VERSION: MPAC 4.00 ON APOLLO FORTRAN 8.40     ******
******                                                             ******
*************************************************************************
*************************************************************************
*************************************************************************

                                                           *************
                                                           * 07/05/88  *
                                                           * 15:50:54  *
                                                           *************


 **********************************
 ************* TASK 1 *************
 **********************************
 ******                     ******
 ******   *MPAC READ PLANT  ******
 ******                     ******
 **********************************
 ************* TASK 1 *************
 **********************************

 *** MODEL READ FROM FILE:  LAT2.MDL ***

 ELAPSED TIME (SEC):       0.24
```

```
***********************************************
******************* TASK 2 ********************
***********************************************
******                                  ******
******    *COMPUTE EIGENVALUES OF PLANT  ******
******                                  ******
***********************************************
******************* TASK 2 ********************
***********************************************
```

SAMPLING TIME : DELTA = 0.0000

******** EIGENVALUES OF PLANT ***********************

COUNT	REAL PART	IMAG PART	DAMPING	FREQ (RAD/S)	FREQ (HZ)
1	0.0000	0.0000	0.0000	0.0000	0.0000
2	-1.2989E-02	0.0000	1.000	1.2989E-02	2.0673E-03
3	-0.1403	1.676	8.3426E-02	1.682	0.2677
4	-0.1403	-1.676	8.3426E-02	1.682	0.2677
5	-1.946	0.0000	1.000	1.946	0.3097

ELAPSED TIME (SEC): 0.14

```
*******************************
*********** TASK 3 ************
*******************************
******                  ******
******   *DEFINE PLANT   ******
******                  ******
*******************************
*********** TASK 3 ************
*******************************
```

```
 ******************************
DELETED   STATE   PSI
CREATED   STATE   BETA_INT.:    1.000    BETA
CREATED   OUTPUT  PHI_CRIT:     1.000    PHI.         5.000    PHI
CREATED   OUTPUT  BETA_CRIT:    1.000    BETA.        3.200    BETA
 ******************************
```

ELAPSED TIME (SEC): 0.10

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```
*************************************************
****************** TASK 4 *******************
*************************************************
******                                    ******
******    *DESIGN GAIN MATRIX FOR PLANT   ******
******                                    ******
*************************************************
****************** TASK 4 *******************
*************************************************
```

DESIGN PARAMETERS:

ALPHA = 1.00000E-03

CONTROL VARIABLE	CONTROL WEIGHT (R)
AIL	1.0000
RUD	2.0000

CRITERIA VARIABLE	CRITERIA WEIGHT (Q)
PHI_CRIT	4.0000
BETA_CRIT	1.0000

===== STEADY STATE RICCATI SOLUTION =====

	1	2	3	4	5
1	15.95	-2.100	-6.876	-5.891	9.802
2	-2.100	1.105	4.050	0.7099	-0.3128
3	-6.876	4.050	15.73	2.397	-2.262
4	-5.891	0.7099	2.397	3.222	-3.365
5	9.802	-0.3128	-2.262	-3.365	14.39

SAMPLING TIME : DELTA = 0.0000

******** EIGENVALUES OF A + B*G ********************
******** OPTIMAL CL EIGENVALUES *******************

COUNT	REAL PART	IMAG PART	DAMPING	FREQ (RAD/S)	FREQ (HZ)
1	-0.9492	0.0000	1.000	0.9492	0.1511
2	-1.574	1.453	0.7346	2.142	0.3409
3	-1.574	-1.453	0.7346	2.142	0.3409
4	-4.442	2.532	0.8688	5.113	0.8138
5	-4.442	-2.532	0.8688	5.113	0.8138

===== FEEDBACK GAIN MATRIX =====

	BETA	P	PHI	R	BETA_INT
AIL	5.470	-2.605	-9.524	-2.000	1.093
RUD	-3.065	-0.5127	-2.059	2.056	-2.722

ELAPSED TIME (SEC): 1.17

```
***********************************************
****************** TASK 5 ******************
***********************************************
******                                   ******
******    *CREATE CONTROLLER FOR PLANT   ******
******                                   ******
***********************************************
****************** TASK 5 ******************
***********************************************

***********************************************************
***** FULL STATE FEEDBACK CONTROLLER *****
***** NO MODEL FOLLOWING *****
***** DIRECT F.B. STATES TO PLANT *****
BETA            P              PHI            R              BETA_INT
***********************************************************

ELAPSED TIME (SEC):      0.50

*******************************************
**************** TASK 6 ****************
*******************************************
******                              ******
******    *FORM PLANT + CONTROLLER  ******
******                              ******
*******************************************
**************** TASK 6 ****************
*******************************************

***********************************************************
***** FULL STATE FEEDBACK CONTROLLER *****
***** NO MODEL FOLLOWING *****
***********************************************************

ELAPSED TIME (SEC):      2.16
```

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```
*******************************************
**************** TASK 7 *****************
*******************************************
******                               ******
******   *PRINT CLOSED-LOOP SYSTEM   ******
******                               ******
*******************************************
**************** TASK 7 *****************
*******************************************

***************************************************************
  ***** CLOSED LOOP SYSTEM *****
***************************************************************
```

SAMPLING TIME : DELTA = 0.0000

=============
===== A =====
=============

	BETA	P	PHI	R	BETA_INT
BETA	-0.2401	5.9648E-02	-4.8458E-02	-0.9132	-0.1075
P	-4.579	-8.932	-25.99	2.8649E-02	-3.112
PHI	0.0000	1.000	0.0000	8.7813E-02	0.0000
R	7.526	0.4025	2.215	-3.809	4.611
BETA_INT	1.000	0.0000	0.0000	0.0000	0.0000

=============
===== B =====
=============

	AIL	RUD
BETA	2.5320E-03	4.0504E-02
P	2.284	2.060
PHI	0.0000	0.0000
R	0.1228	-1.645
BETA_INT	0.0000	0.0000

=============
===== C =====
=============

	BETA	P	PHI	R	BETA_INT
PHI_CRIT	0.0000	1.000	5.000	8.7813E-02	0.0000
BETA_CRIT	2.960	5.9648E-02	-4.8458E-02	-0.9132	3.892
AIL+	5.470	-2.605	-9.524	-2.000	1.093
RUD+	-3.065	-0.5127	-2.059	2.056	-2.722
AIL=	5.470	-2.605	-9.524	-2.000	1.093
RUD=	-3.065	-0.5127	-2.059	2.056	-2.722

=============
===== D =====
=============

	AIL	RUD
PHI_CRIT	0.0000	0.0000
BETA_CRIT	2.5320E-03	4.0504E-02
AIL+	0.0000	0.0000
RUD+	0.0000	0.0000
AIL=	1.000	0.0000
RUD=	0.0000	1.000

ELAPSED TIME (SEC): 0.12

```
*************************************************************
************************** TASK 8 **************************
*************************************************************
******                                                 ******
******   *COMPUTE EIGENVALUES OF CLOSED-LOOP SYSTEM    ******
******                                                 ******
*************************************************************
************************** TASK 8 **************************
*************************************************************
```

SAMPLING TIME : DELTA = 0.0000

******** EIGENVALUES OF CLOSED-LOOP SYSTEM **********

COUNT	REAL PART	IMAG PART	DAMPING	FREQ (RAD/S)	FREQ (HZ)
1	-0.9492	0.0000	1.000	0.9492	0.1511
2	-1.574	1.453	0.7346	2.142	0.3409
3	-1.574	-1.453	0.7346	2.142	0.3409
4	-4.442	2.532	0.8688	5.113	0.8138
5	-4.442	-2.532	0.8688	5.113	0.8138

ELAPSED TIME (SEC): 0.18

```
************************************************
******************** TASK 9 ********************
************************************************
******                                    ******
******   *MPAC WRITE CLOSED-LOOP SYSTEM   ******
******                                    ******
************************************************
******************** TASK 9 ********************
************************************************
```

*** MODEL WRITTEN TO FILE: CLOSED_LOOP.MDL ***

ELAPSED TIME (SEC): 0.32

TOTAL JOB ELAPSED TIME (SEC): 10.24

PROPOSED SIPE TOOLBOX

A Graphic/Engineering Software Concept for Modeling

Amir A. Anissipour

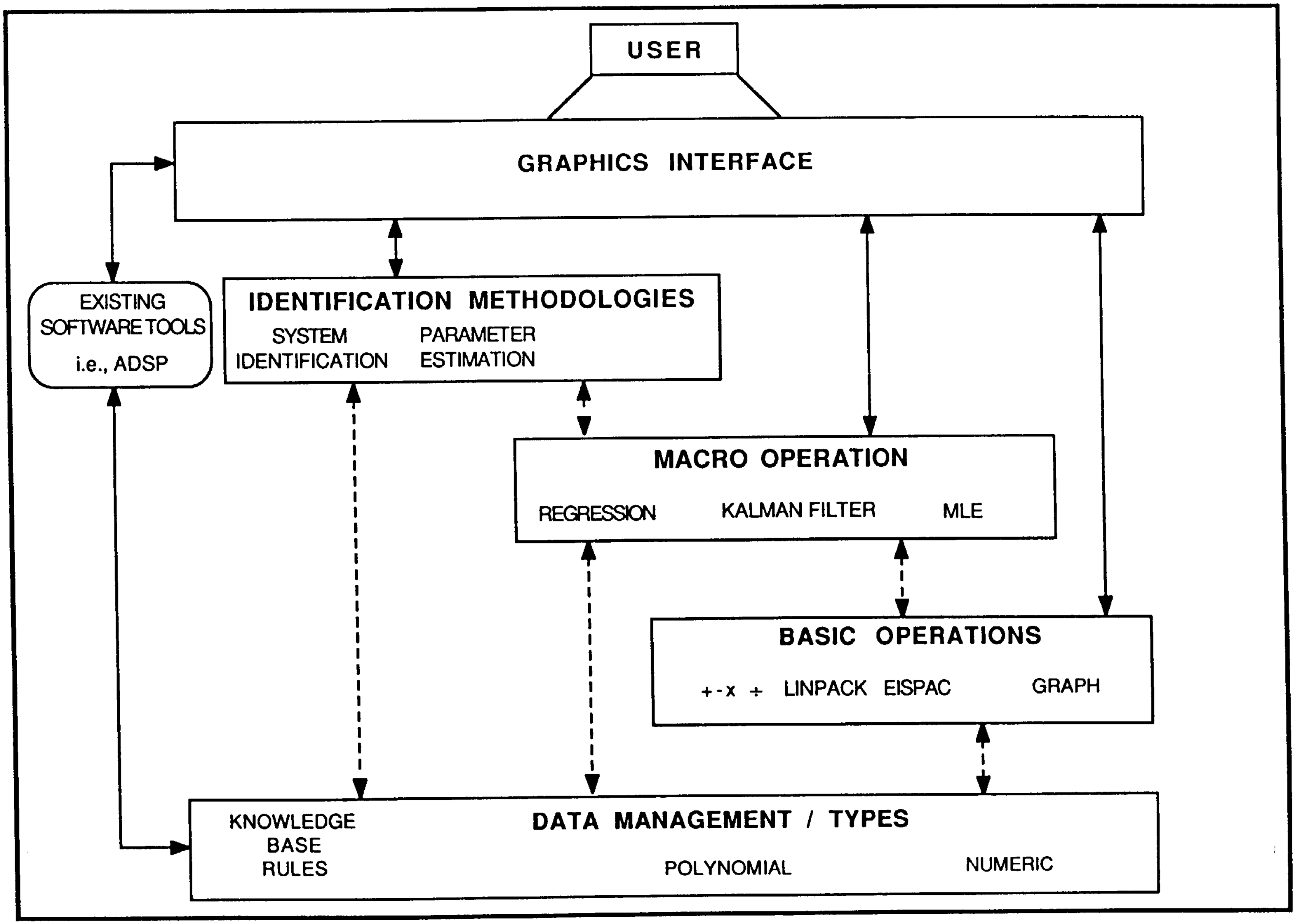
The Boeing Company
Boeing Commercial Airplanes
P.O. Box 3707
Seattle, Washington 98124-2207

CONCEPT OBJECTIVES

CREATE A SUPERIOR COMPUTATIONAL FRAMEWORK FOR MODELING

- SUPPORT LINEAR AND NON-LINEAR SYSTEM MODELS
- HANDEL HIGH-ORDER MODELS
- BASIS FOR FUTURE ENHANCEMENTS
- USER DEFIEND ANALYSIS
- CONSOLIDATE NASA DRYDEN AND NASA LARC METHODS
- INTERACTIVE GRAPHICS ENVIROMENT FOR HIGH PRODUCTIVITY AND VISIBILITY

SIPE TOOLBOX ARCHITECTURE



AAA-88-5