Flixan Introduction

Background

The dynamic behavior of flight vehicles, such as: launch vehicles, reentry vehicles, and high performance aircraft, is generally studied in two distinct phases. The first phase deals with orbital mechanics and flight trajectory optimization assuming that the vehicle can be perfectly steered. This analysis is usually referred to as *"long period dynamics"*. The second study deals with variations of the vehicle from its flight trajectory and they have a relatively shorter period. One of the central features in aerospace vehicles is the development of simulation models of its dynamic behavior. The mathematical model consists of dynamic equations that characterize the vehicle expected behavior and describe how it will respond to wind-gust disturbances and to control commands. The equations of motion are expressed in two forms: (a) the non-linear large angle equations suitable for six-degrees-of-freedom (6-DOF) simulations, and (b) the linearized equations that capture the shorter period dynamics and they describe small variations of the vehicle from its trim condition. The dynamic models are used by the stability and control engineer to develop control laws that allow a human pilot or an autopilot to maneuver the vehicle and to perform its mission.

Flixan is a collection of modeling programs and utilities and its purpose is to provide the capability of creating state-space dynamic models for different types of flight vehicles at fixed flight conditions. It was motivated by the need to develop models of various conceptual flight vehicles, fast and at different levels of complexity. The modeling details depend on the availability of data. It can be varied from simple rigid-body models to very complex models that include high order dynamics, such as: actuators, tail-wags-dog, hinge-moments, wind-gusts, fuel sloshing, flexibility and aero-elasticity, including hundreds of structural modes. The degree of model complexity is defined in the input data and in the options selected there. The designer may begin with a simple rigid model and gradually include more details to increase its complexity as additional parameters become available, such as: actuator, engines, aerosurfaces, flexibility data, slosh, etc. The vehicle configuration is defined in the input data which consists of: mass properties, aerodynamic data, trajectory data, engine data, slosh parameters, aerosurfaces, hinge moment coefficients, aero-elastic coefficients, control moment gyros, reaction wheels, different types of sensors, etc. The models are used for control analysis, robustness analysis, simulations and flight control design. The flight vehicles, either atmospheric or spacecraft, are defined at selected flight conditions and may include airplanes, gliders, launch and re-entry vehicles, rocket-planes, missiles, satellites, space-stations, or any type of generic vehicle consisting of blended features from the above vehicles.

The Flixan program runs under MS Windows and it is highly interactive using dialogs, menus and mouse driven graphics to interface with the analyst. It consists of many program options and utilities for creating and analyzing flight control systems. One of its main features is the flight vehicle modeling program that generates linear flight vehicle state-space systems for airplanes, gliders, launch vehicles, rocket-planes, missiles, spacecraft, etc. The dynamic models may include and can combine different types of effectors together, such as: gimbaling engines (TVC), throttling (variable thrust) engines, reaction control jets (RCS), control aerosurfaces, reaction wheels (RW), control moment gyros (CMG), or any combination of the above for trimming and control. The vehicle model may also include different types of sensors, such as: gyros, rate-gyros, accelerometers, position sensors, and vanes that measure the angles of attack and sideslip. The sensors can be located anywhere on the vehicle and they also measure local structural motion. The number and types of effectors and sensors are defined in the vehicle input data. The vehicle configuration is defined by the input data that consist of: mass properties, aerodynamic data, trajectory data, engine data, slosh parameters, aero-surface data, hinge moment coefficients, aero-elastic coefficients, CMG, reaction wheel data, sensor types, etc. The dynamic models can implement multiple types of flight vehicle concepts, as described in the examples.

The Flixan package includes additional programs and utilities which are related to flight control analysis. There is an actuator modeling program for generating dynamic models of different types of actuators. The actuators rotate the TVC engines and aerosurfaces against disturbance torques and they must be coupled with the vehicle model. An effector mixing logic program is included which calculates a matrix to combine different types of effectors together. This effectors combination matrix converts the flight control system demands (roll, pitch, yaw, etc.) to effector deflections or throttle commands. It optimizes the efficiency of the effectors as a system by maximizing the control authority and reducing the interaction between control directions. The algorithm uses vehicle data, engine thrusts and locations, and aerosurface coefficients. The mixing logic is included in the control software and it connects between the flight control system and the effector inputs. There is also a tool for generating dynamic models for analyzing the flight control system robustness to parameter uncertainties, used in μ-analysis or μ-synthesis. The vehicle internal uncertainties are first defined in the input data file. They are "pulled-out" of the dynamic model and are included as an external block which is connected with the dynamic model with some additional inputs and outputs. This augmented plant model is used in the μ-analysis. There are also utilities for processing modal data and for selecting dominant structural modes based on actuator and sensor placement.

The Flixan package also includes programs for analyzing the vehicle static stability, controllability and performance. Proper static analysis of a new vehicle concept is very important. It allows us to evaluate its controllability and performance fast, and before we get into the control analysis, design and simulations. It includes a Trim program for trimming the vehicle effectors and balancing the moments along a pre-defined trajectory. There is also a static performance analysis program that analyzes static performance based on vehicle data. It calculates parameters such as: static stability, time-to-double amplitude, control authority, etc. along the trajectory. The performance parameters help us evaluate the vehicle concept and how to modify it in order to satisfy the requirements. The static analysis package also includes tools for analyzing static performance and control authority by means of interactive graphics, such as vector diagrams and contour plots. It also provides the capability of graphically selecting flight conditions and generating linear state-space models for further control analysis.

Flixan also includes utilities for combining systems and transfer-functions together. The flight vehicle system often needs to be combined with actuator models, sensor dynamics, an effector combination matrix or TVC, and a flight control system (FCS). There is a systems combination utility that interconnects several state-space systems and matrices together to generate a combined state-space system. There is a similar utility that combines transfer functions together to create state-space systems. There are also utilities that modify and rearrange systems or extract subsystems from bigger systems for the purpose of decoupling pitch and lateral dynamics or creating reduced models for LQR or H-infinity control design. There are utilities for z-transforming continuous systems to discrete state-difference systems, and for managing data files. There are also utilities for reading modal data and for selecting a smaller set of dominant flex modes from big Nastran files. There are also utilities for converting systems and matrices to Matlab format in order to be loaded into Matlab for further analysis. The various utility programs are selected from the Flixan main menu and they are interactive.

The Flixan program operates by using mainly two types of files: input data files that have a filename (*.Inp), and system files with a filename (*.Qdr), where “*” is a short filename that usually identifies the vehicle flight condition, the Mach#, angle of attack, etc. The input file includes the input data-sets to be processed by the corresponding Flixan utilities. The systems file contains the systems and matrices which are generated by the Flixan program. The filenames must be less than 20 characters long. A pair of input and system files (*.Inp and *.Qdr) is created for every vehicle or flight condition to be analyzed. It is a good practice to use the same filename for each project, only the filename extensions are different, for example, "X43-MaxQ.Inp" and "X43-MaxQ.Qdr". The systems file may contain multiple systems or matrices associated with the same vehicle project. The files associated with a particular project are placed in the same directory folder which is typically named after the vehicle name, the flight condition or a project name.

Input data files (.Inp) contain sets of data or instructions that correspond to and are processed by Flixan utilities. Each input data file is usually associated with a particular vehicle analysis or a specific project, and it may contain multiple sets of data that correspond to different utilities, such as: flight vehicle data, actuator data, parameter uncertainties, system interconnections, transfer-function interconnections, system modifications, z-transforms, batch processing instructions, instructions for generating effector mixing logic, etc. Each data-set in the file is processed by a program which creates a state-space system or an individual matrix. The first line in each data-set defines the type of input data and the program that is intended to process the data-set. For example: "BATCH MODE INSTRUCTIONS", "INTERCONNECTION OF SYSTEMS", "FLIGHT VEHICLE INPUT DATA", "ACTUATOR INPUT DATA", or "MIXING LOGIC", etc. The second line is a unique title (which should be less than 100 characters long). It defines the system or matrix that will be created from a specific data-set in the input file. The same title is also used by the program to label the system or the matrix that was created by the data-set, in (*.Qdr) file. The lines below the title, beginning with (!) are comment lines which are optional and they are defined by the user. They are notes describing in more detail the purpose of the model, analysis conditions, or any other comments or information that the user may wish to include for documentation purposes. Each comment line should be less than 100 characters long. The user is not expected to create the input data files from scratch, but there are interactive utilities in most Flixan programs that guide the user in entering the input data and in the preparation of the input data-sets, such as, the vehicle, actuator, interconnections, etc. The parameters entered are saved by the program in the input data file defined. However, sometimes it may be faster to create the input data-set by editing or copying a previously created input data file (.Inp) instead of running the interactive utility of the corresponding program.

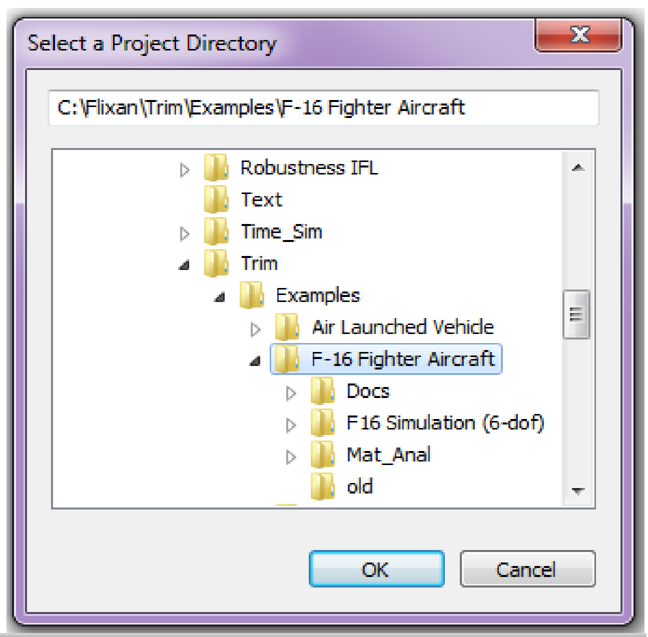
The system files are generated by Flixan and they have an extension (.Qdr). They include datasets consisting of state-space systems defined by four matrices (a, b, c, d), or they may contain individual matrices. Each dataset is created by a Flixan program or utility. A systems file may contain multiple types of systems, such as: simple rigid-body models or very complex high order models. It may also contain different types of actuator models for aero-surfaces or gimbaling engines, flight control systems or sensor dynamics which are originally defined in terms of transfer-function combinations and they are converted into state-space systems by the transfer-functions combination program. The systems file may also contain systems synthesized by combining smaller subsystems using the systems combination utility program or smaller systems extracted from bigger systems. It may also include discrete systems derived from continuous systems by the z-transformation utility. The systems file may also contain individual matrices, such as: gains or TVC matrices, generated, for example, by the mixing logic program. Samples of input and system files are shown below.

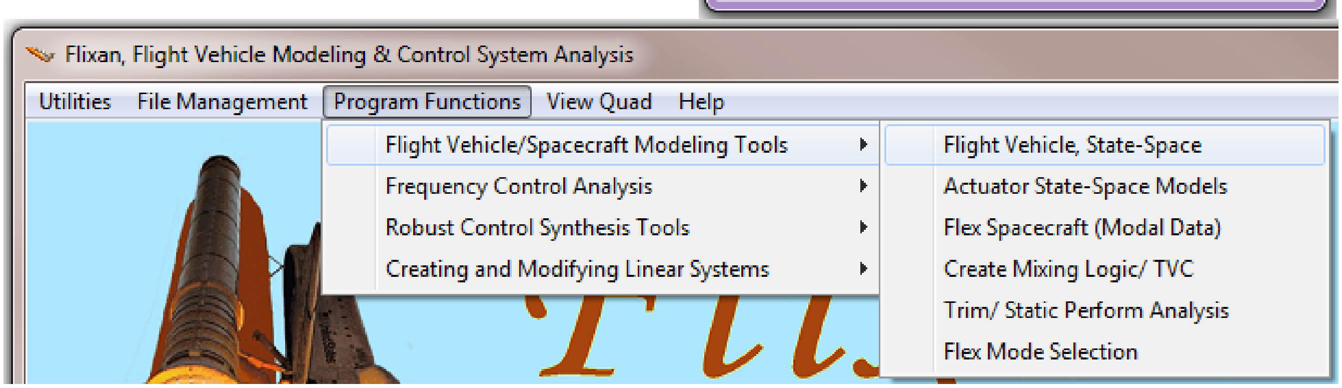
Other files used by Flixan are modal data files (.Mod) that contain modal data generated from a finite-elements program, Node files (.Nod) that contain lists of locations in the structural model used by interactive utilities, and aero-elasticity files (.Gaf) that contain aeroelastic coefficients and inertial coupling parameters. These files are processed by modal data selection and modal data preparation utilities that prepare a set of selected modes to be combined with the vehicle model, as we shall see in the examples.

The following topics will be discussed in the upcoming sections. Section 2 describes the equations of motion used to create generic type of flight vehicle models which are controlled by aerosurfaces, TVC, throttling engines, RCS jets, reaction wheels, and CMGs. The equations are presented in two forms: (a) non-linear, large angle form used in 6-DOF time domain simulations, and (b) linear form that represent variations from trim conditions and used for flight control analysis. In Section 3 we present equations of motion for rigid spacecraft controlled by reaction control jets, reaction wheels, and control moment gyros that can be implemented in Flixan. Section 4 describes the flight vehicle modeling program that includes both: atmospheric vehicles and spacecraft. Section 5 describes the flexible spacecraft modeling program. Section 6 describes typical electro-mechanical and hydraulic actuator models that provide the control torque required to rotate the TVC engines and the aero-surfaces about their hinges. In Section 7 we present a pseudo-inverse method for deriving a mixing-logic matrix that combines different types of effectors together for flight vehicle control. In Section 8 we describe the Internal Feedback Loop (IFL) modeling method used for developing dynamic models for analyzing vehicle robustness to parameter uncertainties by μ-analysis.

Running the Flixan Program

To run the Flixan program, click on the Flixan icon to load the application: "*Flixan.Exe*", and from the folder selection menu, select the location where the input file: (.Inp), the systems file: (.Qdr), and other data files related to your current project are located. Then from the Flixan Main Menu which is at the top of the window select "Program Functions" and then one of the program options to run, as shown below.





Input Data File

The following is an example of an input data file consisting of a number of datasets. Each dataset in the input file can be processed individually by running the corresponding interactive Flixan utility programs, one at a time. However, the entire file can be processed faster by running a batch set which is typically located at the top of the input file. A batch dataset will process the entire input file in batch mode, instead of interactively. A batch set is shown below. It is identified with an ID line "BATCH MODE INSTRUCTIONS" located at the top of the set, shown in red below. The second line is the title of the batch, shown in blue. It may also include some comments, shown in green. The processing instructions are below the comment lines. Each instruction consists of the title of a data-set to be processed by a utility. The data-set is already created and saved in the input file. The program or utility that will process the data-set is included on the left side of the title, as shown below in red. A display comes up while the batch is running showing the processing status and highlighting the current data-set being processed.

```
BATCH MODE INSTRUCTIONS ...............
Batch for calculating the Closed-Loop model for a Zulu Rocket
! This batch set creates a state-space model for a rigid Zulu rocket during first stage
! at Max-Q and then extracts the longitudinal subsystem. It creates also a flex vehicle
! model with fuel sloshing and extracts also the longitudinal flex subsystem.
! It creates also state-space systems for the angle of attack estimator, the flight
! control system, and the closed-loop system. The state-space systems are converted to
! Matlab format.
Flight Vehicle   : Zulu, Stage-1, Max-Q, Rigid Body
System Modificat : Zulu, Stage-1, Max-Q, Rigid Body, Pitch Axis
Flight Vehicle   : Zulu, Stage-1, Max-Q, 8 Flex Modes with Slosh
System Modificat : Zulu, Stage-1, Max-Q, 8 Flex Modes with Slosh, Pitch Axis
Transf-Function  : Alpha Estimator
Transf-Function  : Pitch Flight Control System
System Connection: Pitch Closed-Loop System
To Matlab Format : Zulu, Stage-1, Max-Q, Rigid Body, Pitch Axis
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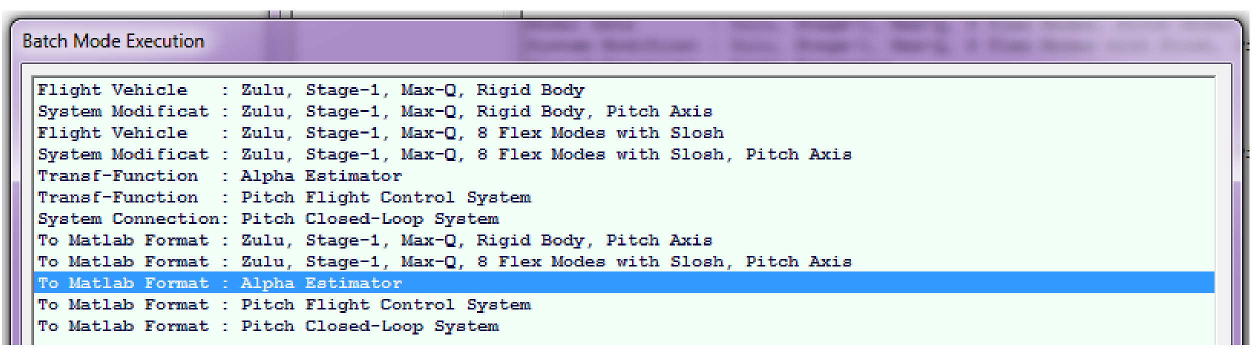

Vehicle Data: The data-set below is a set of flight vehicle data to be processed by the vehicle modeling program. It begins with an ID line, shown in red, the vehicle tittle, in blue, which is a Zulu, first stage rocket, at Max-Q. It includes flexibility and propellant sloshing. Then we have some comment lines (shown in green) that describe the vehicle and the flight condition analyzed. The next line is a set of flags associated with the type of model to be created. Then we have a group of data that includes: mass properties, trajectory parameters, and aerodynamic coefficients, followed by data that define the two TVC engines (thrusts, gimbal locations, etc.). There are no aero-surfaces in this example. The next group of data defines the rate gyro sensors and their locations on the vehicle. We also have two accelerometers measuring in the Y and Z directions and their locations are defined in vehicle axes. The next group of data defines the two propellant sloshing resonances, which include: slosh masses, slosh frequencies, damping, and slosh mass locations. The last line defines structural flexibility. In this vehicle we shall include 8 flex modes that will be read by the program from a set of selected modal data. The selected modal data is in the same input file and its title is “Zulu, Stage-1, Max-Q, 8 Flex Pitch Modes”, shown next.

```
FLIGHT VEHICLE INPUT DATA ......
Zulu, Stage-1, Max-Q, 8 Flex Modes with Slosh
! This is a Launch Vehicle during First Stage at Maximum Dynamic Pressure. It is launched from
! a high altitude to maximize orbit performance. At Max-Q and while flying at 2.5 Mach it
! experiences a strong wind shear that causes 4 deg of angle of attack. The vehicle has two side
! liquid oxygen rockets that can provide 320,000 (lb) of thrust each. The two fuel tanks, one
! on each side cause a significant amount of slosh disturbance.
!
Body Axes Output, Attitude=Euler Angles, Without GAFD, No Turn Coordination

Vehicle Mass (lb-sec^2/ft), Gravity Accelerat. (g) (ft/sec^2), Earth Radius (Re) (ft)    :   8878.0       32.174       0.20896E+08
Moments and products of Inertias Ixx, Iyy, Izz, Ixy, Ixz, Iyz, in (lb-sec^2-ft)          :   519500.0    1671000.0     2110000.0     0.0000
CG location with respect to the Vehicle Reference Point, Xcg, Ycg, Zcg, in (feet)        :  -126.05       0.0000       0.007
Vehicle Mach Number, Velocity Vo (ft/sec), Dynamic Pressure (psf), Altitude (feet)       :   2.5          2000.0       220.00        83000.
Inertial Acceleration Vo_dot, Sensed Body Axes Accelerations Ax,Ay,Az (ft/sec^2)         :   62.000       54.000       0.0000        21.000
Angles of Attack and Sideslip (deg), alpha, beta rates (deg/sec)                         :   4.0000       0.0000       0.0000        0.0000
Vehicle Attitude Euler Angles, Phi_o,Thet_o,Psi_o (deg), Body Rates Po,Qo,Ro (deg/sec)   :   0.0000       44.000       0.0000        0.0000
Wind Gust Vel wrt Vehi (Azim & Elev) angles (deg), or Force(lb), Torque(ft-lb), locat:xyz:   Gust         45.0         45.0
Surface Reference Area (feet^2), Mean Aerodynamic Chord (ft), Wing Span in (feet)        :   47.3         7.7000       7.7000
Aero Moment Reference Center (Xmrc,Ymrc,Zmrc) Location in (ft), {Partial_rho/ Partial_H} :  -127.2        0.0000       0.0000        0.0000
Aero Force Coef/Deriv (1/deg), Along -X, {Cao,Ca_alf,PCa/PV,PCa/Ph,Ca_alfdot,Ca_q,Ca_bet}:   0.63         0.001        0.0000        0.0000
Aero Force Coeffic/Derivat (1/deg), Along Y, {Cyo,Cy_bet,Cy_r,Cy_alf,Cy_p,Cy_betdot,Cy_V}:   0.0         -0.06         0.0000        0.0000
Aero Force Coeff/Deriv (1/deg), Along Z, {Czo,Cz_alf,Cz_q,Cz_bet,PCz/Ph,Cz_alfdot,PCz/PV}:  -1.1         -0.31         0.0000        0.0000
Aero Moment Coeffic/Derivat (1/deg), Roll: {Clo, Cl_beta, Cl_betdot, Cl_p, Cl_r, Cl_alfa}:   0.0         -0.005        0.0000        0.0000
Aero Moment Coeff/Deriv (1/deg), Pitch: {Cmo,Cm_alfa,Cm_alfdot,Cm_bet,Cm_q,PCm/PV,PCm/Ph}:   2.3          0.6          0.0000        0.0000
Aero Moment Coeffic/Derivat (1/deg), Yaw : {Cno, Cn_beta, Cn_betdot, Cn_p, Cn_r, Cn_alfa}:   0.0         -0.26         0.0000        0.0000

Number of Control Surfaces, With or No TWD (Tail-Wags-Dog and Hinge Moment Dynamics) ?   :  0   NO TWD
Number of Thruster Engines, Include or Not the Tail-Wags-Dog and Load-Torque Dynamics ?  :  2   WITH TWD

TVC Engine No:  1                                (Gimbaling  Throttling   Single_Gimbal) : Left TVC         Gimbaling
Engine Nominal Thrust, and Maximum Thrust in (lb)   (for throttling)                     :  320000.0      320000.0
Mounting Angles wrt Vehicle (Dyn,Dzn), Maximum Deflections from Mount (Dymax,Dzmax) (deg):   0.5          0.0          5.0     5.0
Eng Mass (slug), Inertia about Gimbal (lb-sec^2-ft), Moment Arm, engine CG to gimbal (ft):   47.0         260.00       0.2
Gimbal location with respect to the Vehicle Reference Axes, Xgimb, Ygimb, Zgimb, in (ft) :  -144.6       -8.7          0.0

TVC Engine No:  2                                (Gimbaling  Throttling   Single_Gimbal) : Right TVC        Gimbaling
Engine Nominal Thrust, and Maximum Thrust in (lb)   (for throttling)                     :  320000.0      320000.0
Mounting Angles wrt Vehicle (Dyn,Dzn), Maximum Deflections from Mount (Dymax,Dzmax) (deg):   0.5          0.0          5.0     5.0
Eng Mass (slug), Inertia about Gimbal (lb-sec^2-ft), Moment Arm, engine CG to gimbal (ft):   47.0         260.00       0.2
Gimbal location with respect to the Vehicle Reference Axes, Xgimb, Ygimb, Zgimb, in (ft) :  -144.6        8.7          0.0

Number of Gyros, (Attitude and Rate)                                                     :  3
Gyro No  1 Axis:(Pitch,Yaw,Roll), (Attitude, Rate, Accelerat), Sensor Location in (feet) :  Roll   Rate          -102.00      0.00      0.00
Gyro No  2 Axis:(Pitch,Yaw,Roll), (Attitude, Rate, Accelerat), Sensor Location in (feet) :  Pitch  Rate          -102.00      0.00      0.00
Gyro No  3 Axis:(Pitch,Yaw,Roll), (Attitude, Rate, Accelerat), Sensor Location in (feet) :  Yaw    Rate          -102.00      0.00      0.00

Number of Accelerometers, Along Axis: (x,y,z)                                            :  2
Acceleromet No  1 Axis:(X,Y,Z), (Position, Velocity, Acceleration), Sensor Location (ft) :  Y-axis Accelerat.    -102.00      0.00      0.00
Acceleromet No  2 Axis:(X,Y,Z), (Position, Velocity, Acceleration), Sensor Location (ft) :  Z-axis Accelerat.    -102.00      0.00      0.00

Number of Vane Sensors, (Measuring Alpha or Beta)                                        :  0

Number of Slosh Modes                                                                    :  2
Left Tank (slug), Frequ Wy,Wz at 1g (rad/s), Damping (zeta-y-z), Locat {Xsl,Ysl,Zsl} (ft):  350.0   2.31  2.31  0.001  0.001  -135.00  -8.7000
Rght Tank (slug), Frequ Wy,Wz at 1g (rad/s), Damping (zeta-y-z), Locat {Xsl,Ysl,Zsl} (ft):  350.0   2.31  2.31  0.001  0.001  -135.00   8.7000

Number of Bending Modes                                                                  :  8
Zulu, Stage-1, Max-Q, 8 Flex Modes, Pitch Modes
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Modal Data: The next set of data is a group of selected modes which are located in the same input file and they will be combined with the vehicle data to create the flexible vehicle dynamic system. It has a red ID line on the top which identifies the data as a collection of structural modes, followed by the blue title of the modal data set. Then we have some comment green lines that describe the nature of the structural modes and how they were created from the full set of modes that were generated from a finite elements program. Then we show the modal data of the first two modes, beginning with the frequency, damping coefficient, and the modal mass. They are followed by the 3 mode shapes and the 3 modal slopes at different locations on the vehicle. The locations include the 2 gimbals, the 3 gyro sensors, the 2 accelerometers, the locations of the two slosh masses, and a point to be used for a disturbance excitation.

```
SELECTED MODAL DATA AND LOCATIONS FOR THE PITCH MODES
Zulu, Stage-1, Max-Q, 8 Flex Modes, Pitch Modes
! The pitch modes were selected by applying +Z forces at the two gimbals, (same direction at the
! left and right TVC). The pitch rotation was sensed at the IMU node. We included also modal data
! at the two TVC gimbals, the 3 roll, pitch, and yaw gyros, and the two (Ny and Nz) acceleromet.
! The modal data were scaled from the original Nastran output in (*.mod) file. We reverse the
! directions in the X and Z axes. The modal slopes were multiplied by 12 to be converted from
! (rad/inch) to (radians/foot). The modal masses were multiplied by 12 to be converted from
! (snails) to (slugs). Standard Nastran to GN&C units transformation (Default).

MODE # 1/  1, Frequency (rad/sec), Damping (zeta), Generalized Mass=    20.449       0.50000E-02    12.000
DEFINITION OF LOCATIONS (NODES)             phi along X   phi along Y   phi along Z   sigm about X  sigm about Y  sigm about Z

                              Node ID#     Modal Data at the  2 Engines, (x,y,z)...
Left  (-y) Boster Gimbal Locat   35701    -0.25060D-01   0.10089D-01  -0.48000D-03   0.23400D-04  -0.24816D-04  -0.12228D-02
Right (+y) Boster Gimbal Locat   45701     0.25080D-01   0.10093D-01  -0.98000D-04   0.22764D-04  -0.21000D-04  -0.12233D-02

                              Node ID#     Modal Data at the  3 Gyros ...
Nav Base (IMU , Accelerom)       95602    -0.13080D-05   0.23100D-01   0.18520D-03  -0.60120D-04   0.17244D-04   0.36600D-02
Nav Base (IMU , Accelerom)       95602    -0.13080D-05   0.23100D-01   0.18520D-03  -0.60120D-04   0.17244D-04   0.36600D-02
Nav Base (IMU , Accelerom)       95602    -0.13080D-05   0.23100D-01   0.18520D-03  -0.60120D-04   0.17244D-04   0.36600D-02

                              Node ID#     Modal Data at the  2 Accelerometers, along (x,y,z)...
Nav Base (IMU , Accelerom)       95602    -0.13080D-05   0.23100D-01   0.18520D-03
Nav Base (IMU , Accelerom)       95602    -0.13080D-05   0.23100D-01   0.18520D-03

                              Node ID#     Modal Data at the  2 Slosh Masses...
Left  Booster Liquid Oxygen Sl   81602    -0.90090D-02   0.51000D-02   0.26000D-03  -0.33480D-05   0.24360D-04   0.26904D-02
Right Booster Liquid Oxygen Sl   88603     0.90170D-02   0.50960D-02   0.34470D-03  -0.40680D-05  -0.83160D-05   0.26904D-02

                              Node ID#     Modal Data at the Disturbance Point
Nav Base (IMU , Accelerom)       95602    -0.13080D-05   0.23100D-01   0.18520D-03  -0.60120D-04   0.17244D-04   0.36600D-02

MODE # 2/  2, Frequency (rad/sec), Damping (zeta), Generalized Mass=    22.271       0.50000E-02    12.000
DEFINITION OF LOCATIONS (NODES)             phi along X   phi along Y   phi along Z   sigm about X  sigm about Y  sigm about Z

                              Node ID#     Modal Data at the  2 Engines, (x,y,z)...
Left  (-y) Boster Gimbal Locat   35701    -0.26580D-03   0.57370D-04   0.25310D-01   0.12300D-03  -0.19884D-02  -0.15852D-04
Right (+y) Boster Gimbal Locat   45701     0.41850D-03   0.88360D-04   0.25260D-01   0.11760D-03  -0.19872D-02  -0.18912D-04

                              Node ID#     Modal Data at the  3 Gyros ...
Nav Base (IMU , Accelerom)       95602     0.43500D-03   0.45400D-03  -0.10500D-01   0.43200D-05  -0.23088D-02   0.54600D-04
Nav Base (IMU , Accelerom)       95602     0.43500D-03   0.45400D-03  -0.10500D-01   0.43200D-05  -0.23088D-02   0.54600D-04
Nav Base (IMU , Accelerom)       95602     0.43500D-03   0.45400D-03  -0.10500D-01   0.43200D-05  -0.23088D-02   0.54600D-04

                              Node ID#     Modal Data at the  2 Accelerometers, along (x,y,z)...
Nav Base (IMU , Accelerom)       95602     0.43500D-03   0.45400D-03  -0.10500D-01
Nav Base (IMU , Accelerom)       95602     0.43500D-03   0.45400D-03  -0.10500D-01

                              Node ID#     Modal Data at the  2 Slosh Masses...
Left  Booster Liquid Oxygen Sl   81602    -0.12800D-03   0.12550D-03  -0.24500D-01  -0.32760D-04  -0.11892D-02   0.13236D-04
Right Booster Liquid Oxygen Sl   88603     0.15130D-03   0.28260D-03  -0.24510D-01   0.37200D-04  -0.81360D-03   0.70200D-04

                              Node ID#     Modal Data at the Disturbance Point
Nav Base (IMU , Accelerom)       95602     0.43500D-03   0.45400D-03  -0.10500D-01   0.43200D-05  -0.23088D-02   0.54600D-04
--------------------------------------------------------------------------------------------------------------------------------
```

Combination of Systems: Below we show a systems interconnection data-set example that defines the interconnection of 3 systems to create a bigger system with a title "Pitch Closed-Loop System". The titles of the 3 systems to be combined are below the green comment lines, followed by the interconnection instructions. The definitions of the combined system's input and output variables are shown at the bottom of the set.

```
INTERCONNECTION OF SYSTEMS .....
Pitch Closed-Loop System
! Closed-Loop System obtained using the Flixan system building utilities
! to be used for Simulations
Titles of Systems to be Combined
Title 1 Zulu, Stage-1, Max-Q, 8 Flex Modes with Slosh, Pitch Axis
Title 2 Alpha Estimator
Title 3 Pitch Flight Control System
SYSTEM INPUTS TO SUBSYSTEM  3      Pitch Flight Control System
System Input  1 to Subsystem  3, Input  1, Gain=  -1.0000                 Theta Command
System Input  2 to Subsystem  3, Input  4, Gain=  -1.0000                 Gamma Command
......................................................................
SYSTEM INPUTS TO SUBSYSTEM  1      Zulu, Stage-1, Max-Q, 8 Flex Modes with Slos
System Input  3 to Subsystem  1, Input  5, Gain=   1.0000                 Wind Gust (ft/sec)
......................................................................
SYSTEM OUTPUTS FROM SUBSYSTEM  1   Zulu, Stage-1, Max-Q, 8 Flex Modes with Slosh
System Output  1 from Subsystem  1, Output  1, Gain=   1.0000             Theta
System Output  2 from Subsystem  1, Output  4, Gain=   1.0000             q-flex (rate gyro)
System Output  3 from Subsystem  1, Output  3, Gain=   1.0000             Alpha
System Output  5 from Subsystem  1, Output  1, Gain=   1.0000             Gamma= Theta
System Output  5 from Subsystem  1, Output  3, Gain=  -1.0000                   -Alpha
System Output  6 from Subsystem  1, Output  5, Gain=   1.0000             Nz accelerom
......................................................................
SYSTEM OUTPUTS FROM SUBSYSTEM  2   Alpha Estimator
System Output  4 from Subsystem  2, Output  1, Gain=   1.0000             Alpha-Hat
......................................................................
SYSTEM OUTPUTS FROM SUBSYSTEM  3   Pitch Flight Control System
System Output  7 from Subsystem  3, Output  1, Gain=   1.0000             Gimbal deflect (rad)
......................................................................
SUBSYSTEM NO  1 GOES TO SUBSYSTEM NO  3                                   Vehicle to Controller
Subsystem  1, Output  1 to Subsystem  3, Input  1, Gain=   1.0000         Attitude Theta
Subsystem  1, Output  4 to Subsystem  3, Input  2, Gain=   1.0000         q-flex
Subsystem  1, Output  1 to Subsystem  3, Input  4, Gain=   1.0000         Gamma= Theta
Subsystem  1, Output  3 to Subsystem  3, Input  4, Gain=  -1.0000               -Alpha
......................................................................
SUBSYSTEM NO  1 GOES TO SUBSYSTEM NO  2                                   Vehicle to Estimator
Subsystem  1, Output  4 to Subsystem  2, Input  3, Gain=   1.0000         q-flex
Subsystem  1, Output  5 to Subsystem  2, Input  1, Gain=   1.0000         Nz
......................................................................
SUBSYSTEM NO  2 GOES TO SUBSYSTEM NO  3                                   Estimator to Controller
Subsystem  2, Output  1 to Subsystem  3, Input  3, Gain=   1.0000         Alpha-Estimate
......................................................................
SUBSYSTEM NO  3 GOES TO SUBSYSTEM NO  1                                   Gimbal to Vehicle
Subsystem  3, Output  1 to Subsystem  1, Input  1, Gain=   1.0000         Pitch Gimbal-1
Subsystem  3, Output  1 to Subsystem  1, Input  2, Gain=   1.0000         Pitch Gimbal-2
......................................................................
SUBSYSTEM NO  3 GOES TO SUBSYSTEM NO  2                                   Gimbal to Estimator
Subsystem  3, Output  1 to Subsystem  2, Input  2, Gain=   1.0000         Pitch Gimbal
......................................................................
Definitions of Inputs  =   3
Theta Command (rad)
Gamma Command (rad)
Wind Gust Veloc. (ft/sec)

Definitions of Outputs =   7
Theta (rad)
Pitch Rate (rad/sec)
Alpha (rad)
Alpha Estimate (rad)
Gamma (rad)
Normal Accelerometer, Nz (ft/sec^2)
Gimbal Deflection (rad)
----------------------------------------------------------------------------------------------------------
```

<u>Transfer-Function Combination</u>: The two next data-sets are transfer-function interconnections, describing systems of transfer functions. They will be processed by a utility that combines the blocks together into state-space systems with titles "Alpha Estimator", and "Pitch Flight Control System". The transfer functions to be combined are located below the comments and the interconnection instructions are below them. The definitions of the combined system input and output variables are included at the bottom of the sets.

```
SYSTEM OF TRANSFER FUNCTIONS ...
Alpha Estimator
! This filter estimates the angle of attack in (radians) from the accelerometer measurement and
! the gimbal deflection angle. It basically solves the normal force equation for alpha. The
! inputs are (a) Nz measurement from the accelerometer, (b) Pitch rate to counteract against the
! rotational component picked up by the accelerometer, (c) gimbal deflection to estimate the
! normal component of thrust. The washout filter differentiates the rate gyro signal at low
! frequencies.
Continuous
TF. Block #  1 Integrator                               Order of Numer, Denom=   0  1
Numer 0.0     1.0
Denom 1.0     0.0
TF. Block #  2 Washout Filter                           Order of Numer, Denom=   1  1
Numer 280.0   0.0
Denom 1.0    10.0
....................................................................................................
Block #, from Input #, Gain
   1   1   -8878.000        {TF:  1, Integrator  } from {Nz Acceleration}
   1   2   -464000.0        {TF:  1, Integrator  } from {Gimbal Deflection}
   2   3    1.0             {TF:  2, Washout Filt} from {Pitch Rate Gyro}
...........................
Outpt #, from Block #, Gain
   1   1   0.1745000E-01    {System Output  1    } from {TF:  1, Integrator  }
...........................
Block #, from Block #, Gain
   1   1   -3225.860        {TF:  1, Integrator  } from {TF:  1, Integrator  }
   1   2   -8878.0          {TF:  1, Integrator  } from {TF:  2, Washout Filt}
...........................
Definitions of Inputs  =   3
Nz Acceleration (ft/sec^2)
Gimbal Deflection, Delta (rad)
Pitch Rate Gyro, q-flex (rad/sec)

Definitions of Outputs =   1
Alpha Estimate in (radians)
-------------------------------------------------------------------------------------------------------------

SYSTEM OF TRANSFER FUNCTIONS ...
Pitch Flight Control System
! This is the state-feedback pitch FCS with filters and actuator combined
! The attitude, pitch rate and gamma come from the vehicle subsystem. The
! angle of attack comes from the alpha estimator. The output goes to the
! vehicle gimbal deflection input.
Continuous
TF. Block #  1 Gamma Integrat                           Order of Numer, Denom=   0  1
Numer 0.0    1.0
Denom 1.0    0.0
TF. Block #  2 Low-Pass Filter                          Order of Numer, Denom=   0  2
Numer 0.0    0.0    324.0
Denom 1.0    19.8   324.0
TF. Block #  3 Actuator                                 Order of Numer, Denom=   0  1
Numer 0.0    63.0
Denom 1.0    63.0
....................................................................................................
Block #, from Input #, Gain
   2   1    0.85            {TF: 2, Filter} from {Theta Error}
   2   2    0.5             {TF: 2, Filter} from {Pitch Rate Gyro}
   2   3    0.0125          {TF: 2, Filter} from {Alpha}
   1   4    1.0             {TF: 1, Integrator} from {Gamma Error}
...........................
Outpt #, from Block #, Gain
   1   3    1.0             {Gimbal Deflect} from {TF: 3, Actuator}
...........................
Block #, from Block #, Gain
   3   2    1.0             {TF: 3, Actuator} from {TF: 2, Filter}
   2   1    0.04375         {TF: 2, Filter} from {TF: 1, Gamma Integral}
...........................
Definitions of Inputs  =   4
Theta error (Theta-Thetcom) (rad)
Pitch rate gyro (rad/sec)
Alpha (rad)
Gamma error (Gamma-Gamcom) (rad)

Definitions of Outputs =   1
Gimbal Deflection (radians)
-------------------------------------------------------------------------------------------------------------
```

System Modifications/ Extractions: There are data-sets for modifying an existing system, for example, extracting a pitch or a lateral subsystem from a fully coupled system that was generated by the Flixan program. The data-set includes two system titles (shown in blue). The modified system title is placed above the original system title. The comments should be placed below the 2 titles. The extracted input, state, and output numbers from the original system are included at the bottom of the data-set, as shown.

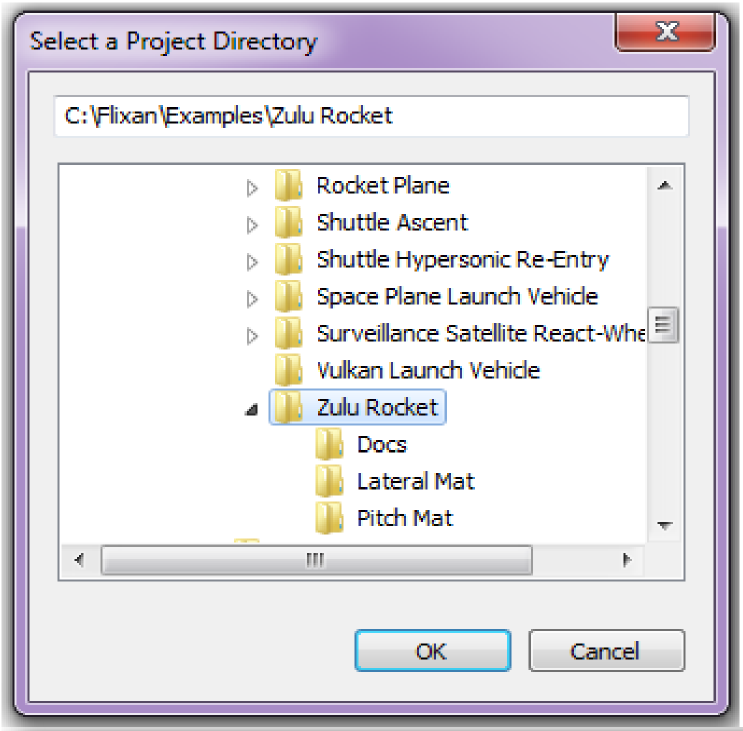
```
----------------------------------------------------------------------------------------------------------------------
CREATE A NEW SYSTEM FROM AN OLD SYSTEM... (Titles of the New and Old Systems)
Zulu, Stage-1, Max-Q, Rigid Body, Pitch Axis
Zulu, Stage-1, Max-Q, Rigid Body
! Pitch rigid system is extracted from the coupled rigid system above
TRUNCATE OR REORDER THE SYSTEM INPUTS, STATES, AND OUTPUTS
Extract Inputs :   1   2   5
Extract States :   3   4   7
Extract Outputs:   3   4   7  14
----------------------------------------------------------------------------------------------------------------------
CREATE A NEW SYSTEM FROM AN OLD SYSTEM... (Titles of the New and Old Systems)
Zulu, Stage-1, Max-Q, 8 Flex Modes with Slosh, Pitch Axis
Zulu, Stage-1, Max-Q, 8 Flex Modes with Slosh
! Pitch flexible system is extracted from the coupled system above
! to be used in Matlab/Simulink Simulations
TRUNCATE OR REORDER THE SYSTEM INPUTS, STATES, AND OUTPUTS
Extract Inputs :   1   2   3   4   9
Extract States :   3   4   7  11  12  13  14  15  16  17  18  19  20  21  22  23  24  25  26  27  29  31  33
Extract Outputs:   3   4   7  13  16  17  18
----------------------------------------------------------------------------------------------------------------------
```

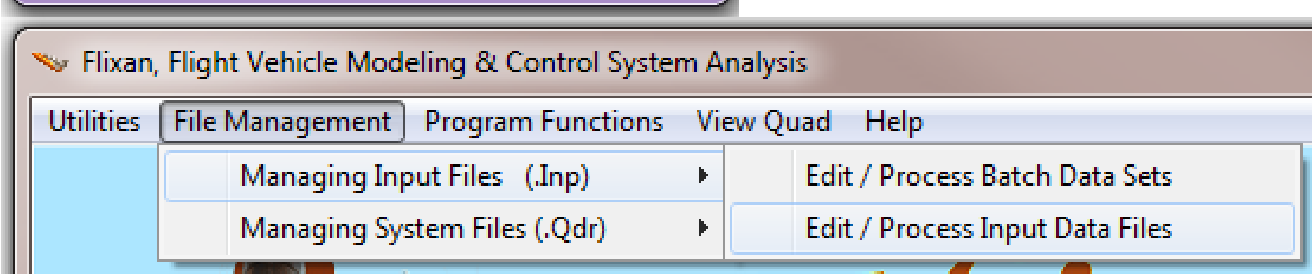
Matlab Conversions: There are also data-sets that read systems or matrices from a Systems file and convert them to Matlab functions that can be loaded into Matlab workspace. The system or matrix titles are shown in blue. The names of the m-file functions to be created are included at the bottom of each set

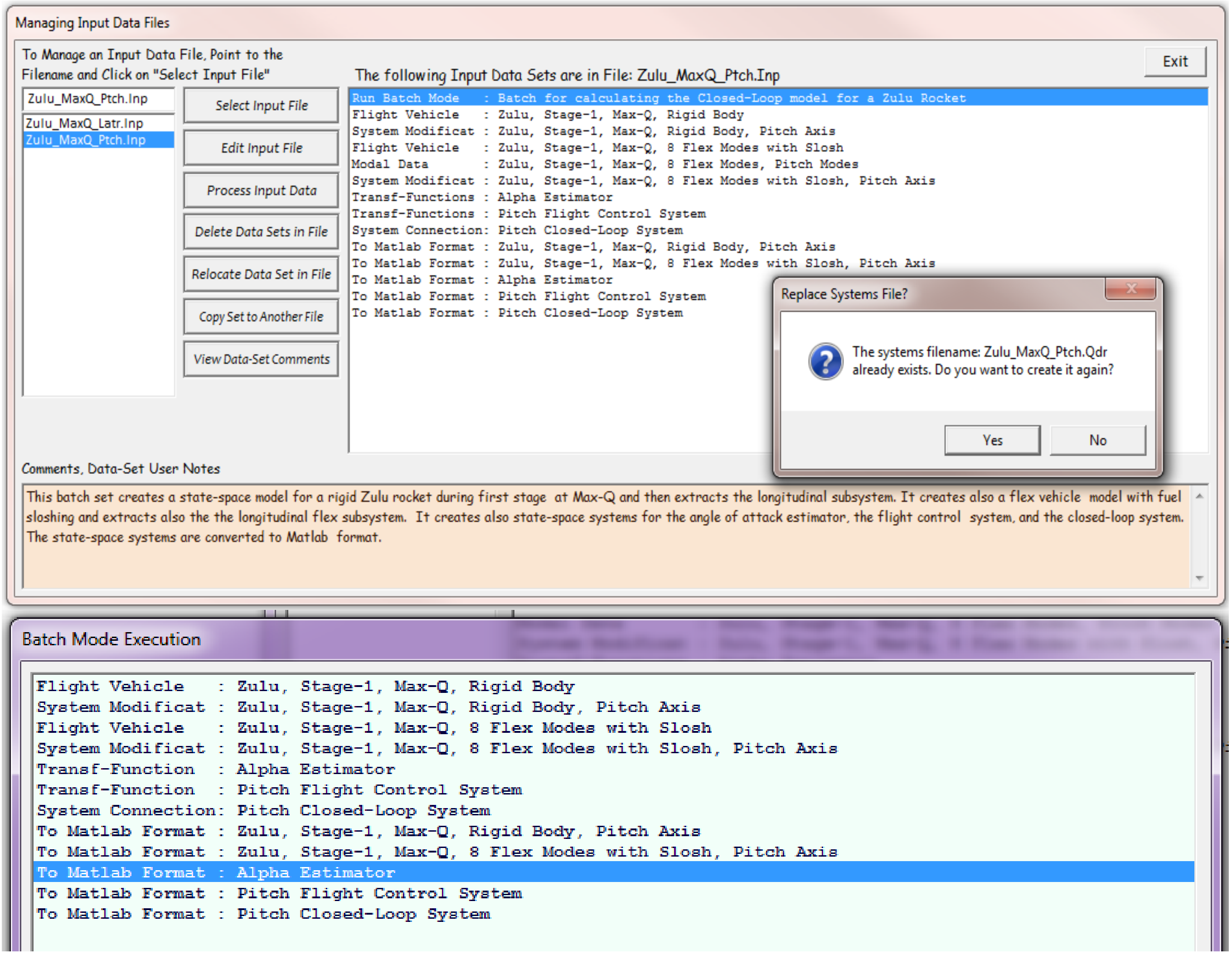
```
CONVERT TO MATLAB FORMAT ........      (Title, System/Matrix, m-filename)
Zulu, Stage-1, Max-Q, Rigid Body, Pitch Axis
System
Vehi_Pitch_rb
---------------------------------------------------------------------------------------------------------------------
CONVERT TO MATLAB FORMAT ........      (Title, System/Matrix, m-filename)
Zulu, Stage-1, Max-Q, 8 Flex Modes with Slosh, Pitch Axis
System
Vehi_Pitch_SFlx
---------------------------------------------------------------------------------------------------------------------
CONVERT TO MATLAB FORMAT ........      (Title, System/Matrix, m-filename)
Alpha Estimator
System
Estimator
---------------------------------------------------------------------------------------------------------------------
CONVERT TO MATLAB FORMAT ........      (Title, System/Matrix, m-filename)
Pitch Flight Control System
System
pitch_fcs
---------------------------------------------------------------------------------------------------------------------
END-END-END-END-END-END-END-END-END-END-END-END-END-END-END-END-END-END-END-END-END-END-END-END-END-
```

Processing an Input Data File

To process an input data file in batch mode, start the Flixan program and select the project directory that contains the input data file: "*C:\Flixan\Examples\Zulu Rocket*". Then go to "*File Management*", "*Manage Input Files*", and select "*Edit/Process/ Input Data Files*". The following dialog is used for managing input data files. The selected folder contains two input data files. Select the file "*Zulu_MaxQ_Ptch.Inp*" from the left menu and click on "*Select Input File*". The menu on the right shows the titles of the data sets which are included in this file. On the left side of each title there is a short label that defines the type of the data-set and the program utility that will process it. On the top of the data-set list there is a batch already created for processing the entire file. To process the batch, you must first click on the top title from the right menu with title: "*Batch for calculating the Closed-Loop model for a Zulu Rocket*", and then click on "*Process Input Data*". The Flixan program will process the input file and save the systems and matrices in file "*Zulu_MaxQ_Ptch*.Qdr". It will also create the matrices and system functions required for Matlab analysis. The bottom window shows the data-sets which are highlighted while they are processed by the batch set. It helps identify possible errors when processing the input file.







Systems File

A systems file has an extension (.Qdr) and contains data of state-space systems or individual matrices that were created by Flixan programs. They are identified as systems or matrices by the first line in the data, shown in red. The system or matrix title (shown in blue) is the same as the title of the data-set from the input file that created it. The comments below the title are also transferred from the input data-set. The system input, state, and output names are defined at the bottom of the state-space matrices.

```
STATE-SPACE SYSTEM ...
ROCKET PLANE AT MACH=0.85, Q=150, T=1778.0 sec (Pitch RB)
! This is a simple Pitch Axis Model
! Extracted from the Coupled Axes Rigid Body Model
! Its inputs, states, and outputs are defined below
!
Number of Inputs, States, Outputs, Sample Time dT (for discrete)=  3  2  3  0.0000
Matrices: (A,B,C,D)
Matrix A                     Size =  2 X  2
         1-Column        2-Column
  1-Row -0.30138585E+00 -0.39838865E+01
  2-Row  0.99731876E+00 -0.29373747E+00
---------------------------------------------------------------------------------
Matrix B                     Size =  2 X  3
         1-Column        2-Column        3-Column
  1-Row -0.36336161E+01 -0.36336161E+01 -0.25937799E-02
  2-Row -0.21435051E-01 -0.21435051E-01 -0.22487362E-03
---------------------------------------------------------------------------------
Matrix C                     Size =  3 X  2
         1-Column        2-Column
  1-Row  0.10000000E+01  0.00000000E+00
  2-Row  0.00000000E+00  0.10000000E+01
  3-Row -0.22074682E+01 -0.25042853E+03
---------------------------------------------------------------------------------
Matrix D                     Size =  3 X  3
         1-Column        2-Column        3-Column
  1-Row  0.00000000E+00  0.00000000E+00  0.00000000E+00
  2-Row  0.00000000E+00  0.00000000E+00  0.83712588E-03
  3-Row -0.17702788E+02 -0.17702788E+02 -0.18556683E+00
---------------------------------------------------------------------------------
Definition of System Variables

Inputs  =   3
  1    Left  Rudder Deflection (rad)
  2    Right Rudder Deflection (rad)
  3    Gust Azim, Elevat Angles=(45,45) (deg)

States  =   2
  1    Pitch Rate        ( q -rigid)    (rad/sec)
  2    Angle of attack   (alfa-rigid)   (radians)

Outputs =   3
  1    Pitch Rate  (q-stab)  (rad/sec)
  2    Angle of attack, alfa, (radians)
  3    CG Acceleration along Z axis, (ft/sec^2)
---------------------------------------------------------------------------------
GAIN MATRIX FOR ...
Shuttle Ascent, Coupled Model, Max_Q T=55 sec
! This is a matrix that was created using the Flixan Mixing Logic program.
! It is a TVC matrix that converts the Roll, Pitch and Yaw acceleration demands from
! flight control to pitch and yaw engine deflection commands. The matrix inputs and
! outputs are defined below.
!
Matrix K2                    Size = 10 X  3
         1-Roll          2-Pitch         3-Yaw
  1-Row  0.00000000E+00 -0.33481212E+00  0.00000000E+00
  2-Row  0.42072877E-01 -0.34527500E+00 -0.76731573E-02
  3-Row -0.42072877E-01 -0.34527500E+00  0.76731573E-02
  4-Row  0.25131532E+00 -0.55578813E+00 -0.45834326E-01
  5-Row -0.25131532E+00 -0.55578813E+00  0.45834326E-01
  6-Row  0.28624342E+00  0.00000000E+00 -0.41166570E+00
  7-Row  0.20227759E+00  0.00000000E+00 -0.40758536E+00
  8-Row  0.20227759E+00  0.00000000E+00 -0.40758536E+00
  9-Row -0.14377220E-01  0.00000000E+00 -0.59408361E+00
 10-Row -0.14377220E-01  0.00000000E+00 -0.59408361E+00
-----------------------------------------------------------------
Definitions of Matrix Inputs (Columns):    3
Roll  Acceleration About Vehicle X Axis
Pitch Acceleration About Vehicle Y Axis
Yaw   Acceleration About Vehicle Z Axis

Definitions of Matrix Outputs (Rows):     10
TVC Output #  1 to Engine No:  1 Pitch Deflect
TVC Output #  2 to Engine No:  2 Pitch Deflect
TVC Output #  3 to Engine No:  3 Pitch Deflect
TVC Output #  4 to Engine No:  4 Pitch Deflect
TVC Output #  5 to Engine No:  5 Pitch Deflect
TVC Output #  6 to Engine No:  1  Yaw  Deflect
TVC Output #  7 to Engine No:  2  Yaw  Deflect
TVC Output #  8 to Engine No:  3  Yaw  Deflect
TVC Output #  9 to Engine No:  4  Yaw  Deflect
TVC Output # 10 to Engine No:  5  Yaw  Deflect
-----------------------------------------------------------------
```