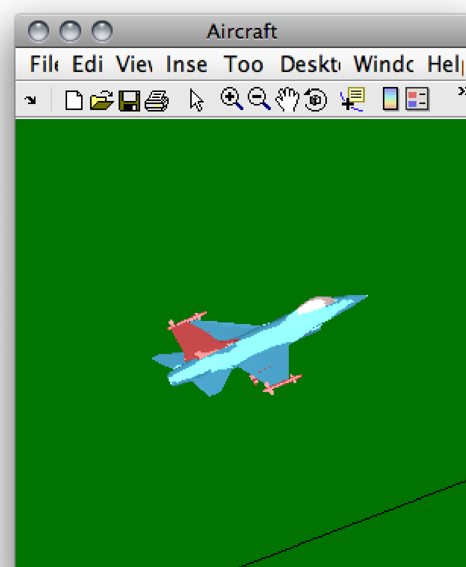
Princeton SATELLITE SYSTEMS

Aircraft Control Toolbox User's Guide



Aircraft Control Toolbox

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CHAPTER 1

Introduction

The Aircraft Control Toolbox is a commercial software product for MATLAB sold by Princeton Satellite Systems. This chapter shows you how to install the Aircraft Control Toolbox and how it is organized.

1.1 Organization

The Aircraft Control Toolbox provides a suite of MATLAB functions designed to assist the aerospace engineer with the design, simulation and performance analysis of aircraft models and and aircraft control systems.

The toolbox code is organized into several different modules, described in the following table. The modules at the top are in both the Academic and Professional Editions, while the modules at the bottom (ACPro and Airships) are in the Professional Edition only.

Table 1.1: Aircraft Control Toolbox

Module	Functionality
AC	Coordinate transformations, aircraft models, integrated simulation, standard atmosphere, aerodynamic property calculations, basic control designs.
AeroUtils	Additional atmosphere models and CAD tools, including wing and fuselage designs.
Common	Engineering constants database, control design and analysis tools, general coordinate transformation routines, graphics and plot utilities, time functions.
Math	vector math operations, trigonometric operations, Newton-Raphson method, Runge-Kutta integration, Simplex, probability analysis tools
Plotting	GUI's for managing, plotting, and animating simulation data.
ACPro	Engine models, flexible dynamics model, more aircraft models, performance analysis tools, point mass trajectory simulation, wind disturbance models.
Airships	Airship modeling and simulation tools.

The "Common" folder contains a large code base that provides the core functionality for both the Aircraft Control Toolbox and its companion product, the Spacecraft Control Toolbox.

1.2 Requirements

MATLAB 2014b at a minimum is required to run all of the functions. Most of the functions will run on previous versions but we are no longer supporting them.

1.3 Installation

The preferred method of delivering the toolbox is a download from the Princeton Satellite Systems website. Put the folder extracted from the archive anywhere on your computer. There is no installer application to do the copying for you. We will refer to the folder containing your modules as PSSToolboxes. You can copy the pdf documentation (located in the Documentation/ folder) anywhere you wish.

All you need to do now is to set the MATLAB path to include the folders in PSSToolboxes. We recommend using the supplied function `PSSSetPaths.m` instead ofMATLAB's path utility. From the MATLAB prompt, cd to your PSSToolboxes folder and then run PSSSetPaths. For example:

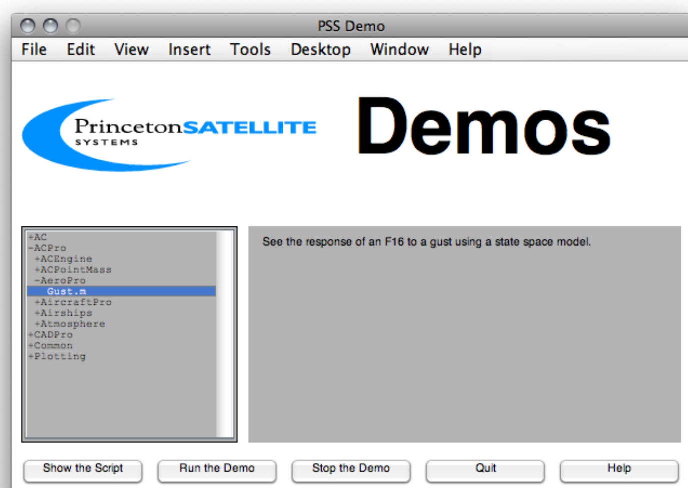
```
>> cd /Users/me/PSSToolboxes
>> PSSSetPaths
```

This will set all of the paths for the duration of the session, with the option of saving the new path for future sessions.

1.4 Getting Started

The first two functions that you should try are `DemoPSS` and `FileHelp`. Each toolbox or module has a Demos folder and a function `DemoPSS`. Do not move or remove this function from any of your modules! `DemoPSS.m` looks for other `DemoPSS` functions to determine where the demos are in the folders so it can display them in the `DemoPSS` GUI. The GUI display in Figure 3.4 on page 18 shows some demos in the Core toolbox.

Figure 1.1: `DemoPSS`

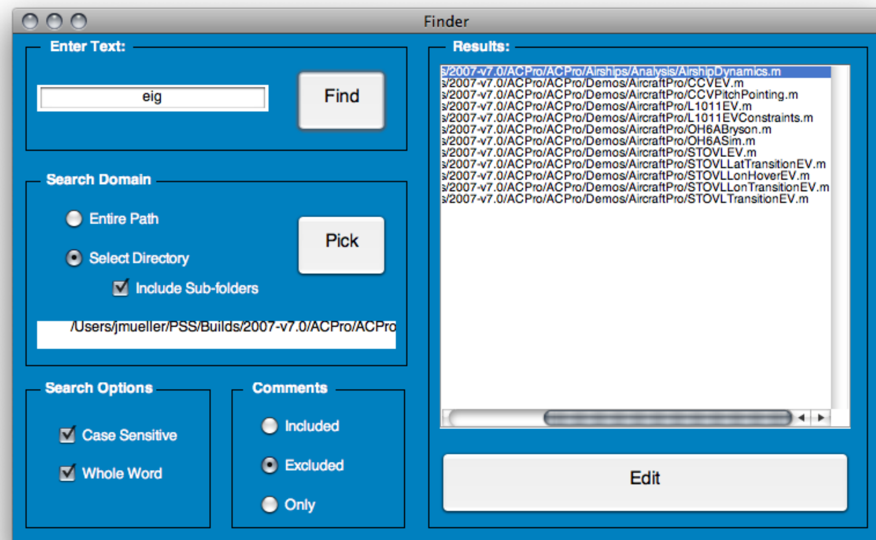


The Common/Control demos are visible in the hierarchical menu to the left. The highest level of this menu shows the folders within the toolbox. You can add your own demo scripts to the demo folders so that they can appear in the display.

The FileHelp function, discussed in more detail in the next chapter, provides a graphical interface to the MATLAB function headers. You can peruse the functions by folder to get a quick sense of your new product's capabilities and search the function names and headers for keywords. FileHelp and DemoPSS provide the best way to get an overview of the Aircraft Control Toolbox.

Another useful search tool is the Finder GUI. Type Finder at the prompt to initialize the GUI. A screenshot is shown in Figure 1.2 on the next page. This tool allows you to search for a string inside non-MATLAB m-files. You can look over the entire path, or pick a single folder. You have the additional option of including all sub-folders recursively in the search. You can decide whether to make the search case sensitive, and whether or not to look for the whole word. Whole words are separated by whitespace or any other non alpha-numeric character. In addition, we have included the nice feature of distinguishing between comments and code. You can search for the string ONLY in comments, ONLY in code, or in both.

Figure 1.2: Finder



CHAPTER 2

FUNDAMENTALS

This chapter gives you some basic information about the toolbox, including the aircraft properties database, classes, and code conventions.

2.1 Aircraft Properties Database

All aircraft properties are stored in databases that can be accessed through text-based commands. The toolbox comes with a predefined database of aircraft properties. The following table lists all of the aircraft databases included in the toolbox.

Table 2.1: Aircraft Properties

File Name	Type	Description
F16.m	Nonlinear	Tables of aerodynamic coefficients for a simplified F16 model
AIRC.m	Statespace	Vertical dynamics for an aircraft
CCV .m	Statepace	Longitudinal dynamics for a control configured vehicle (CCV)
DC8.m	Stability Derivatives	Longitudinal and lateral dynamics.
L1011.m	Statespace	Lateral dynamics for an airliner
0H6A.m	Statespace	Longitudinal and lateral dynamics for a small helicopter in hover.
STOVL.m	Statespace	Longitudinal and lateral dynamics for a Short Take-Off Vertical Landing (STOVL) vehicle in hover and transition modes
F18Model.m	Statespace	Longitudinal and lateral dynamics for an F/A-18 aircraft over a range of altitudes and Mach numbers.
CCVSObel.m	Statespace	CCV longitudinal aircraft model with a pitch pointing mode
A10.m	Statespace	A10 aircraft models: with and without tiltable wing panels.
F100.m	Statespace	Gas Turbine 16th-order F100 linear model: Pratt and Whitney F100-PW-100(3) continuous time model

The properties in a database are accessed by passing a text string to the database function. The text string identifies the set of properties or the dynamic mode that you want to obtain. You can first obtain a list of possible text string identifiers for the database by passing the argument `'catalog'`. For example, to obtain the options for the STOVL.m function:

```
>> STOVL('catalog')
ans =
longitudinal hover
lateral/directional hover
```

```
longitudinal transition
lateral/directional transition
```

Next, to obtain the statespace model associated with longitudinal hover:

```
>> g = STOVL('longitudinal_hover')
g =
        statespace object: 1-by-1
```

You can then obtain information about this object of class `statespace`. For example, you can compute the eigenvalues of the system by simply supplying `g` as an input to the `eig` function:

```
>> eig(g)
ans =
                         0
                    -0.014
          0.30555502572409
        -0.214277512862045 +      0.297241130045908i
        -0.214277512862045 -      0.297241130045908i
                       -50
                        -4
```

See the next section for more information on the `statespace` and `acstate` classes.

The usage of the `F18Model.m` function is slightly different. This database stores an array of longitudinal and lateral-directional dynamic statespace models across a range of flight conditions. It takes as inputs a Mach number and altitude, which define a unique flight condition. The function then returns the statespace model associated with the closest stored Mach number and altitude.

In addition to the aircraft databases listed above, the toolbox also provides the capability to generate dynamic models for airships, or lighter-than-air vehicles. Rather than storing databases of aerodynamic properties, the airship modeling functions allow you to size an airship for operation at a desired altitude, and then automatically generate the mass properties and aerodynamic coefficients for your design. The airship functions are discussed in Section 11 on page 67.

2.2 Classes

The Aircraft Control Toolbox defines and makes use of the following two classes:

- `acstate`
- `statespace`

2.2.1 Class: `acstate`

The `acstate` class defines an aircraft state vector. At a minimum, it stores all of the usual information associated with a dynamic state vector for a rigid body, including the position, velocity, attitude, and body angular rates, as well as the mass, CG location, and moment of inertia. It can also store additional information if necessary, including the angular velocity of rotors, and any number of states for engines, actuator, sensors, flexible dynamics, and disturbance models.

The "help" information on acstate.m explains how to create an `acstate` class object.

```
>> help acstate
 ---------------------------------------------------------------------------
    Create an object of class acstate
```

```
---------------------------------------------------------------------------
   Form:
   x = acstate( r, q, w, v, wR, mass, inertia, cG, engine,
                actuator, sensor, flex, disturb )
---------------------------------------------------------------------------

   ------
   Inputs
   ------
   r       (3,1) ECI position vector
   q       (4,1) Quaternion from ECI to body
   w       (3,1) Inertial body rate in body frame
   v       (3,1) Velocity of cm wrt air
   wR      (:,1) Angular velocity of rotors
   mass    (1,1) Mass
   inertia (6,1) Inertia
   cG      (3,1) Center of mass
   engine  (:,1) Engine states
   actuator(:,1) Actuator states
   sensor  (:,1) Sensor states
   flex    (:,1) Flex model states organized [x;v] by appendage
   disturb (:,1) Disturbance model states

   -------
   Outputs
   -------
   x           (1,1) State vector

---------------------------------------------------------------------------
```

To extract any element of the class, use the `get` method. For example:

```
>> r = get(x,'r');
```

will return the position vector, where `x` is an `acstate` class.

To see a list of all the methods available:

```
>> methods acstate

Methods for class acstate:

abs         get         minus       mtimes      subsasgn   zeros
acstate     length      mrdivide    plus        subsref
```

The `plus` and `minus` methods allow you to add and subtract multiple states. The `mtimes` and `mrdivide` methods allow you to multiply and divide a state by a scalar. These operations can be performed using the standard +,-,*,/ symbols. The `subsasgn` and `subsref` methods allow you to assign and reference elements of the state using the standard MATLAB parenthesis notation. For example:

```
>> r = x(1:3);
```

will also return the position vector. Any element(s) can be assigned this way as well. For example:

```
>> x(8:10) = zeros(3,1);
```

will set the angular rates to zero.

2.2.2 Class: `statespace`

The `statespace` class defines a linear statespace dynamic system. The system can be either continuous or discrete. A continuous system is of the form:

$$\dot{x} = Ax + Bu \tag{2.1}$$

$$y = Cx + Du \tag{2.2}$$

where x is the state vector, A is the state transition matrix, and B is the control effect matrix. Each system type is denoted with a unique string identifier. Continuous systems are denoted with "s".

For a discrete system, there are two different ways to write the state evolution. The first method is shown below, which we call the "z" method:

$$x_{k+1} = Ax_k + Bu_k \tag{2.3}$$
$$y_k = Cx_k + Du_k \tag{2.4}$$

The other discrete method uses the delta operator. This is termed the "delta" method:

$$x_{k+1} = x_k + Ax_k + Bu_k \tag{2.5}$$
$$y_k = Cx_k + Du_k \tag{2.6}$$

A continuous statespace system can be converted to discrete-time by using the `C2DZOH` or `C2DelZOH` methods, which use a zero-order-hold on the input over a specified sampling time. The conversion from continuous to discrete time changes the A and B matrices only. The same C and D matrices are valid for both continuous and discrete domains.

To define a `statespace` class, you must at least specify the A, B, C matrices. If the D matrix is not supplied it is set to all zeros. In addition, you may also supply a name for the system, individual names for the states, inputs, and outputs, the system type, and the time step (if the system is discrete). The "help" information on statespace.m explains how to create an `statespace` class object.

```
>> help statespace
 -------------------------------------------------------------------------------
    Create a state space object. Everything after c is optional.
 -------------------------------------------------------------------------------
    Form:
    g = statespace( a, b, c, d, name, states, inputs, outputs, sType, dT )
 -------------------------------------------------------------------------------

    ------
    Inputs
    ------
    a                           State transition matrix
    b                           State input matrix
    c                           State output matrix
    d                           State feedthrough matrix
    name      (1,:)             Name of the system
    states    (:,:)   or {:}    State  names
    inputs    (:,:)   or {:}    Input names
    outputs   (:,:)   or {:}    Outputs
    sType     (1,:)             's', 'z', 'delta'
    dT        (1,1)             Time step

    -------
    Outputs
    -------
    g                    (:)      Plant
                    g.a        State transition matrix
                    g.b        State input matrix
                    g.c        State output matrix
                    g.d        State feedthrough matrix
                    g.n        Number of states
                    g.nI       Number of inputs
                    g.nO       Number of outputs
                    g.states   Names of states
                    g.inputs   Names of inputs
                    g.outputs  Names of outputs
```

```
                    g.sType   's', 'z', 'delta'
                    g.dT      Time step

 ------------------------------------------------------------------------------
```

You can view the methods associated with the `statespace` class by typing:

```
>> methods statespace

Methods for class statespace:

and          connect      get          getsub       mtimes       series
    statespace
close        eig          getabcd      isempty      plus         set
```

Assume you have a `statespace` class named `g`. You can extract the A, B, C, D matrices from the class by typing:

```
>> [a,b,c,d] = getabcd(g);
```

Similarly, you can extract individual matrices or other information using the `get` method.

```
>> b = get(g,'b');
>> stateNames = get(g,'states');
```

2.3 Code Conventions

It is important to follow consistent code conventions to make the code easy for other people to understand and use. The scripts and functions supplied with this toolbox are always supplied with a descriptive header that provides usage syntax and a list of inputs and outputs. You can type

```
>> help FUNCTION
```

for any function to view the header.

When naming variables, we strive to use meaningful names. We also follow the C convention:

```
word1Word2Word3
```

where the beginning of each word after the first is capitalized. If a word is abbreviated the first letter is not capitalized. For example:

```
rPM
```

is revolutions per minute.

Almost all function names in ACT begin with a capital letter to distinguish them from variables. The only exceptions are class methods, such as `get` and `plus`, for example. These method names overload built-in MATLAB functions for other class methods, and therefore must be all lower case.

Many functions in the Aircraft Control Toolbox can be executed with no inputs, even when inputs are required. If an input is required but not provided, the function may use its own default value. You can see what the default values are by opening the function and examining the lines of code that immediately follow the help comments at the top of the file. For example, consider the AirshipControlDemo.m function. We see from the help header that it is called as follows:

```
%   Form:
%   out = AirshipControlDemo( alpha, beta, V, w0, alt, T, doPlot )
```

This function takes 7 inputs. Examining the file, we see that if no inputs are provided, it uses its own set of default values:

```
if( nargin == 0 )
   alpha = 2*pi/180;
   beta  = 1*pi/180;
   V     = 24;
   w0    = [0;0;0];
   alt   = 21336;
   T     = 100;
   doPlot= [];
end
```

CHAPTER 3

GETTING HELP

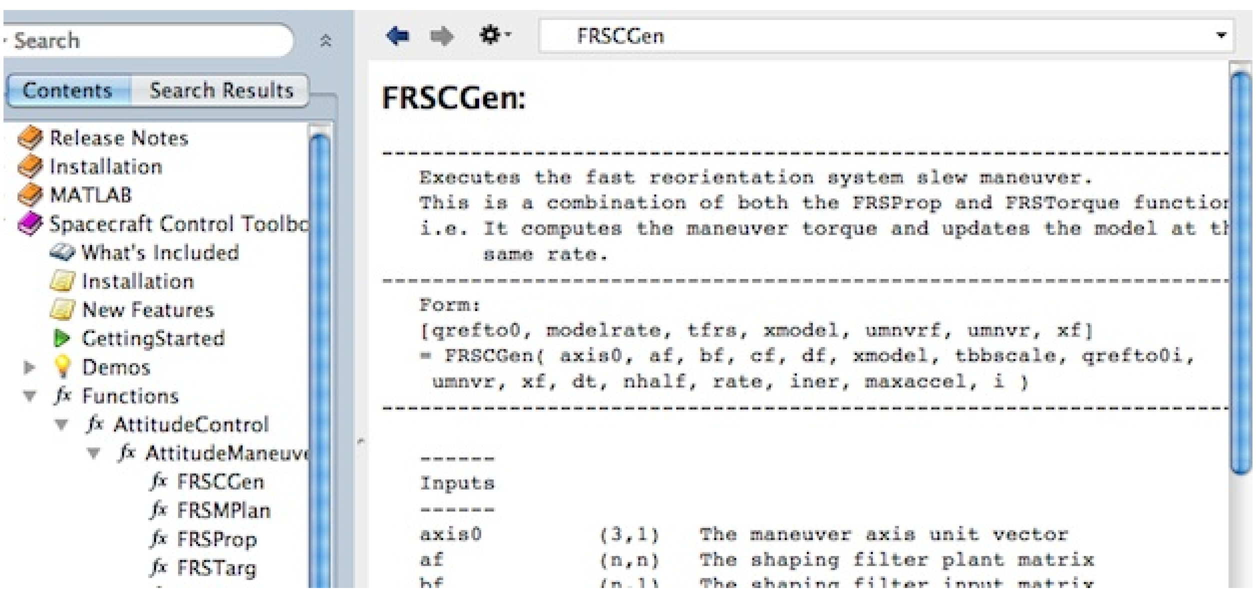
This chapter shows you how to use the help systems built into PSS Toolboxes. There are several sources of help. Our toolboxes are now integrated into MATLAB's built-in help browser. Then, there is the MATLAB help system which prints help comments for individual files and lists the contents of folders. Also, there are special help utilities built into the PSS toolboxes: one is the file help function, the second is the demo functions and the third is the graphical user interface help system. Additionally, you can submit technical support questions through our website and use our web forums to join discussions about the toolboxes.

3.1 MATLAB's Built-in Help System

3.1.1 Basic Information and Function Help

Our toolbox information can now be found in the MATLAB help system. To access this capability, simply open the MATLAB help system. As long as the toolbox is in the MATLAB path, it will appear in the contents pane. Its location is depicted in Figure 3.1 (R2011b and earlier).

Figure 3.1: MATLAB Help

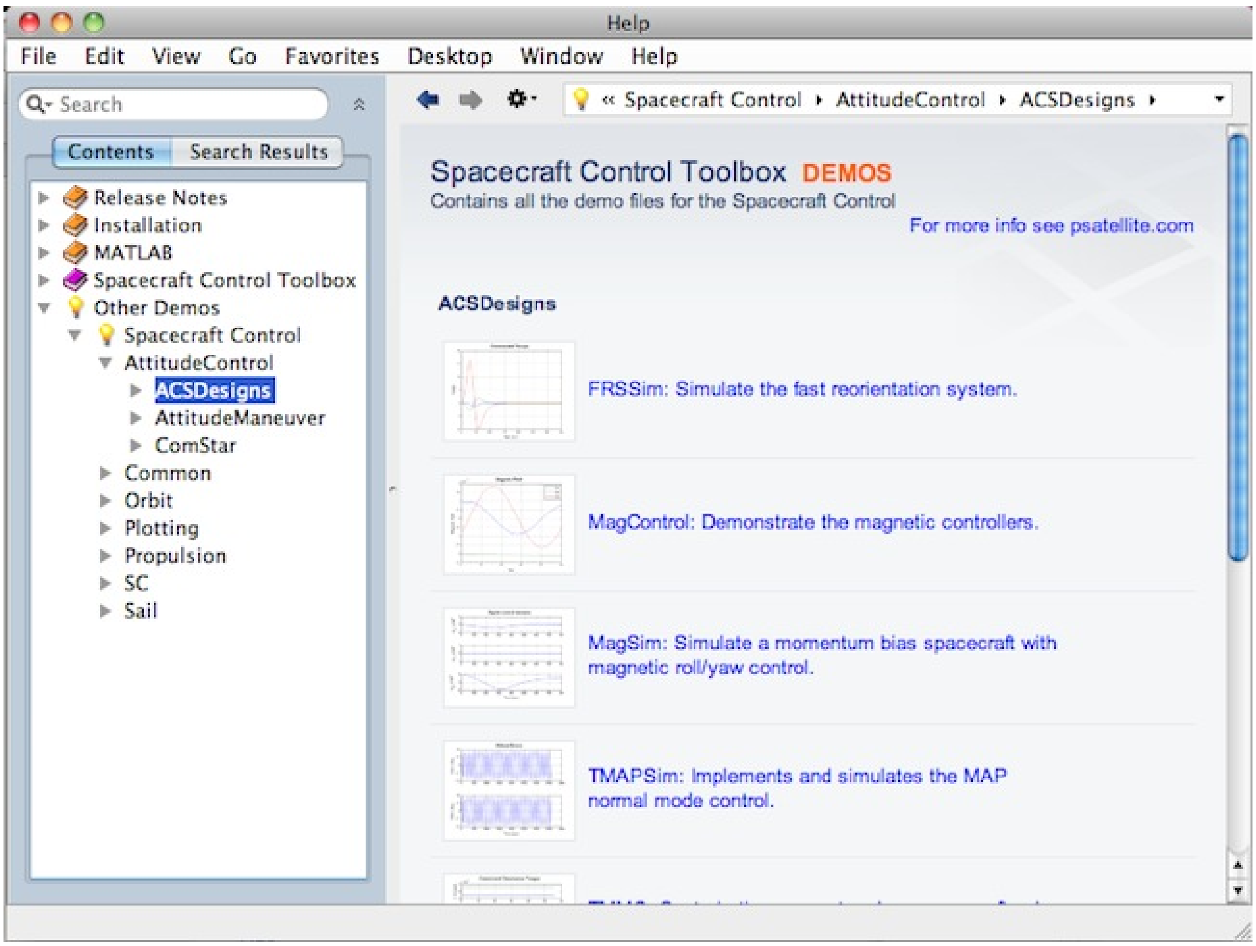


This contains a lot information on the toolbox. It also allows you to search for functions as you would if you were searching for functions in the MATLAB root.

3.1.2 Published Demos

Another feature that has been added to the MATLAB help structure is the access to all of the toolbox demos. Every single demo is now listed, according to module and the folder. These can be found under the *Other Demos* or *Examples* portion of the Contents Pane. Each demo has its own webpage that goes through it step by step showing exactly what the script is doing and which functions it is calling. From each individual demo webpage you can also run the script to view the output, or open it in the editor. Note that you might want to save any changes to the demo under a new file name so that you can always have the original. Below is an example of demo page displayed in MATLAB help that shows where to find the toolbox demos as well as the the hierarchal structure used for browsing the demos.

Figure 3.2: Toolbox Demos



3.2 MATLAB Help

You can get help for any function by typing

```
>> help functionName
```

For example, if you type

```
>> help C2DZOH
```

you will see the following displayed in your MATLAB command window:

```
-----------------------------------------------------------------
    Create a discrete time system from a continuous system
    assuming a zero-order-hold at the input.
    Given
    .
    x = ax + bu

    Find f and g where
     x(k+1) = fx(k) + gu(k)

-----------------------------------------------------------------
    Form:
    [f, g] = C2DZOH( a, b, T )
-----------------------------------------------------------------
    ------
    Inputs
    ------
    a                   Plant matrix
    b                   Input matrix
    T                   Time step
    -------
    Outputs
    -------
    f                   Discrete plant matrix
    g                   Discrete input matrix

-----------------------------------------------------------------
```

All PSS functions have the standard header format shown above. Keep in mind that you can find out which folder a function resides in using the MATLAB command `which`, i.e.

```
>> which C2DZOH
/Software/Toolboxes/Aerospace/Common/Control/C2DZOH.m
```

When you want more information about a folder of interest, remember that you can get a list of the contents in any directory by using the `help` command with a folder name. The returned list of files is organized alphabetically. For example,

```
>> help ACDynamics

  ACDynamics

  A
     AC                                - Dynamics model for an aircraft. Updates
         the data structure x.
     ACBuild                           - Build the aircraft model.
     ACInit                            - Initialize the aircraft model.
     ACPlot                            - Plots the aircraft data. opt is 'info', '
         init', 'store', 'plot'
     ACTrim                            - Aircraft trimming algorithm. Uses the
         function FTrim. This algorithm

  F
     FTrim                             - Cost function for the trimming algorithm

  S
     StateSpacePlot                    - Plots statespace data. opt is 'init', '
         store', 'plot'
```

If there is a folder with the same name in a Demos directory, the demos will be listed separately. For example,

```
>> help AeroPro

  Demos/AeroPro

  G
     Gust                            - See the response of an F16 to a gust using
         a state space model.

  AeroPro

  H
     HorizontalWind                  - Form:

  W
     WindGust                        - Wind gust model. Generates state space
        equations or spectral densities.
```

This type of help also works with higher level directories, for instance if you ask for help on the Common directory, you will get a list of all the subdirectories.

```
  PSS Toolbox Folder Common
  Version 2014.1      11-Jul-2014

  Directories:
  Atmosphere
  Classes
  CommonData
  Control
  ControlGUI
  Database
  DemoFuns
  Demos
  Demos/Control
  Demos/ControlGUI
  Demos/Database
  Demos/General
  Demos/GeneralEstimation
  Demos/Graphics
  Demos/Help
  Demos/MassProperties
  Demos/Plugins
  Demos/UKF
  Estimation
  FileUtils
  General
  Graphics
  Help
  Interface
  MassProperties
  Materials
  Plugins
  Quaternion
  Time
  Transform
```

The function `ver` lists the current version of all your installed toolboxes. Each ACT module that you have installed will be listed separately. For instance,

```
------------------------------------------------------------------------------------

MATLAB Version: 8.1.0.604 (R2013a)
...
------------------------------------------------------------------------------------

MATLAB                                                      Version 8.1        (R2013a)
PSS Toolbox Folder AC                                       Version 2014.1
PSS Toolbox Folder ACPro                                    Version 2014.1
PSS Toolbox Folder AeroUtils                                Version 2014.1
PSS Toolbox Folder Airships                                 Version 2014.1
PSS Toolbox Folder Common                                   Version 2014.1
PSS Toolbox Folder Math                                     Version 2014.1
PSS Toolbox Folder Plotting                                 Version 2014.1
```

3.3 FileHelp

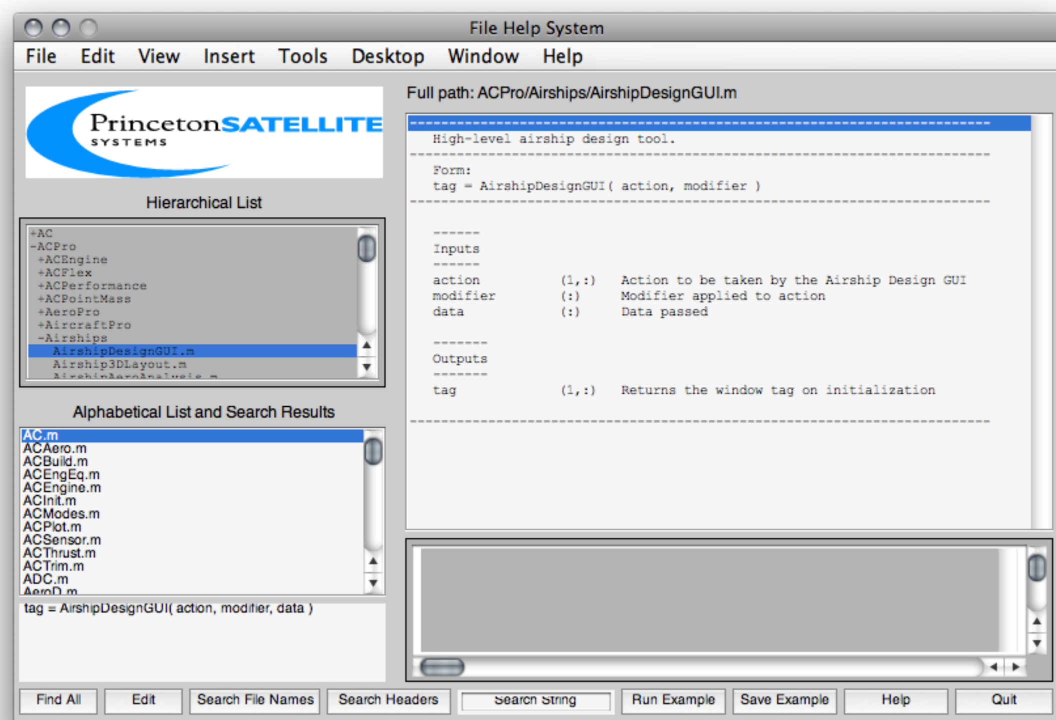
3.3.1 Introduction

When you type

```
FileHelp
```

the FileHelp GUI appears.

Figure 3.3: The file help GUI



There are five main panes in the window. On the left hand side is a display of all functions in the toolbox arranged in the same hierarchy as the PSSToolboxes folder. Scripts, including most of the demos, are not included. Below the hierarchical list is a list in alphabetical order by product. On the right-hand-side is the header display pane. Immediately below the header display is the editable example pane. To its left is a template for the function. You can cut and paste the template into your own functions.

3.3.2 The List Pane

If you click a file in the alphabetical or hierarchical lists, the header will appear in the header pane. This is the same header that is in the file. The headers are extracted from a .mat file so changes you make will not be reflected in the file. In the hierarchical list, any name with a + or - sign is a folder. Click on the folders until you reach the file you would like. When you click a file, the header and template will appear.

3.3.3 Edit Button

This opens the MATLAB edit window for the function selected in the list.

3.3.4 The Example Pane

This pane gives an example for the function displayed. Not all functions have examples. The edit display has scroll bars. You can edit the example, create new examples and save them using the buttons below the display. To run an example, push the Run Example button. You can include comments in the example by using the percent symbol.

3.3.5 Run Example Button

Run the example in the display. Some of the examples are just the name of the function. These are functions with built-in demos. Results will appear either in separate figure windows or in the Matlab Command Window.

3.3.6 Save Example Button

Save the example in the edit window. Pushing this button only saves it in the temporary memory used by the GUI. You can save the example permanently when you Quit.

3.3.7 Help Button

Opens the on-line help system.

3.3.8 Quit

Quit the GUI. If you have edited an example, it will ask you whether you want to save the example before you quit.

3.4 Searching in File Help

3.4.1 Search File Names Button

Type in a function name in the edit box and push Search File Names.

3.4.2 Find All Button

Find All returns to the original list of the functions. This is used after one of the search options has been used.

3.4.3 Search Headers Button

Search headers for a string. This function looks for exact, but not case sensitive, matches. The file display displays all matches. A progress bar gives you an indication of time remaining in the search.

3.4.4 Search String Edit Box

This is the search string. Spaces will be matched so if you type attitude control it will not match attitude control (with two spaces.)

3.5 DemoPSS

If you type `DemoPSS` you will see the GUI in Figure 3.4 on the following page. The list on the left-hand-side is hierarchical and the top level follows the organization of your toolbox modules. Most folders in your modules have matching folders in Demos with scripts that demonstrate the functions. The GUI checks to see which directories are in the same directory as DemoPSS and lists all directories and files. This allows you to add your own directories and demo files.

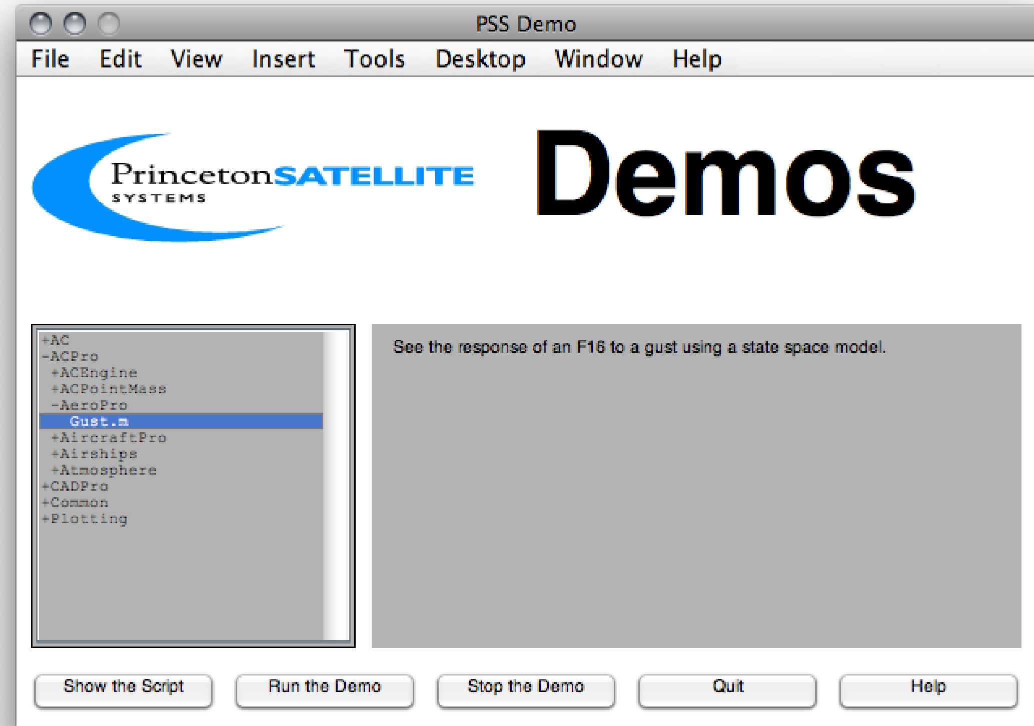
Click on the first name to open the directory. The + sign changes to - and the list changes. Figure 3.4 on the next page shows the ACPro/AeroPro folder, which has one demo: `Gust.m`. The hierarchical menu shows the highest level folders.

Your own demos will appear if they are put in any of the Demos folders. If you would like to look at, or edit, the script, push Show the Script.

3.6 Graphical User Interface Help

Many of the graphical user interfaces (GUI) have a help button. If you hit the help button a new window will appear which displays information about how to use the GUI. You can access on-line help about the GUIs through this display. It is separate from the file help GUI described above. The display is hierarchical. Any list item with a + or - in front is a help heading with multiple subtopics. + means the heading item is closed, - means it is open. Clicking on a heading name toggles it open or closed. Figure 3.5 on page 19 shows the display with the Telemetry help expanded. If you click on a topic in the list you will get a text display in the right-hand pane. You can either search the headings or the text by entering a text string into the Search For edit box and hitting the appropriate button. Restore List restores the list window to its previous configuration.

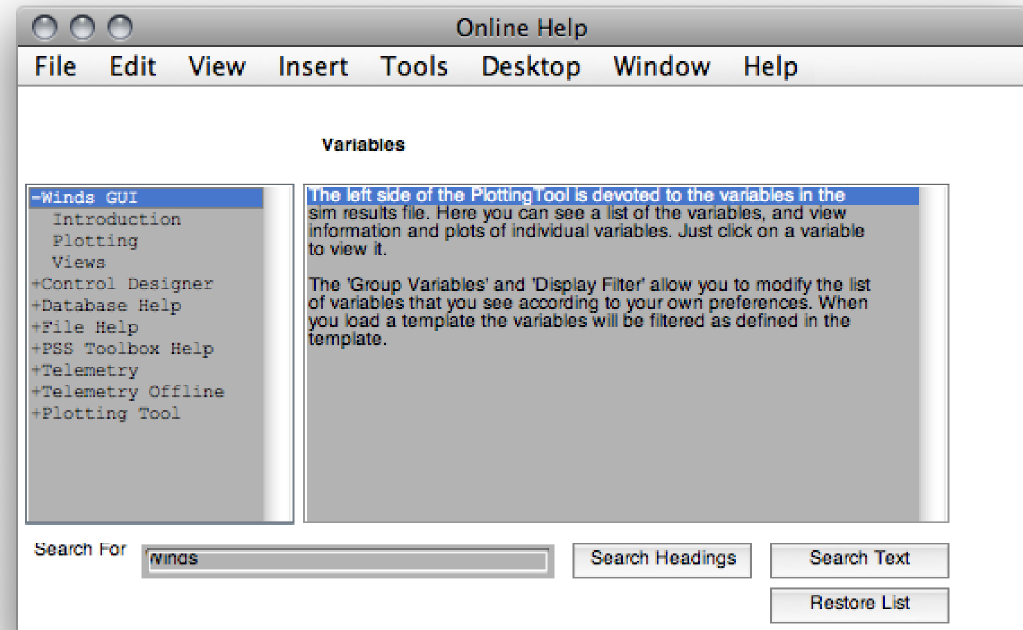
Figure 3.4: The demo GUI



3.7 Technical Support

Contact support@psatellite.com for free email technical support. We are happy to add functions and demos for our customers when asked.

Figure 3.5: On-line Help



CHAPTER 4

Coordinate Transformations

This chapter shows you how to use Aircraft Control Toolbox functions for coordinate transformations.

4.1 Coordinate Frames

The guidance, navigation and control of aircraft require vectors to be expressed in several different coordinate frames. The fundamental coordinate frames of interest are:

- Body-fixed (BODY)
- Stability-axis (STAB)
- Wind-axis (WIND)
- North-East-Down (NED)
- Earth-Centered Inertial (ECI)

Each coordinate frame is an orthogonal right-handed system. The BODY, STAB, and WIND frames are all attached to a fixed point on the aircraft. The NED frame is attached to the surface of the Earth, while the ECI frame is a non-rotating inertial frame attached to the center of the Earth.

In the body-fixed coordinate frame, the x axis points forward out the nose, the y axis points out the right side of the aircraft, and the z axis completes the right-hand-system, pointing locally up. The rotational motion of the aircraft is defined in the body frame as roll, pitch, and yaw about the x, y and z axes, respectively.

In the stability axis system (STAB), the y axis is aligned with the BODY frame y axis. The $x - z$ plane is rotated about the y axis through the angle of attack, α.

We go from STAB frame to the WIND frame by rotating about the z axis through the sideslip angle, β. The result is that the x axis of the WIND frame is aligned exactly with the wind-relative velocity vector. In level flight, with no angle of attack and no sideslip angle, the STAB and WIND frames are both aligned exactly with the BODY frame.

A positive angle of attack rotates the stability x axis down, around the $-y$ axis. A positive sideslip angle rotates the y axis forward, around the $-z$ axis.

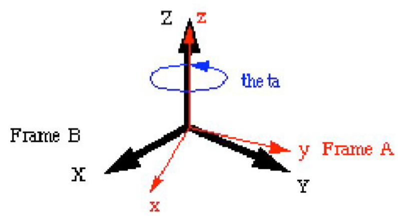
The North-East-Down frame is attached to the surface of the Earth, on the line that connects the center of the Earth to the aircraft. Expressing the aircraft velocity in the NED frame allows us to compute the heading and flight path angles.

The ECI frame is the inertial frame used for integrating the equations of motion.

4.2 Transformation Matrices

Transforming a vector u from its representation in frame A to its representation in frame B is easily done with a transformation matrix. Consider two frames with an angle θ between their x and y axes.

Figure 4.1: Frames A and B




```
uA    = [1;0;0];
theta = pi/6;
m = [ cos(theta),sin(theta),0;...
     -sin(theta),cos(theta),0;...
      0,0,1];
uB = m*uA
```

Using ACT functions, this code can be written as a function of Euler angles:

```
uB = Eul2Mat([0,0,theta])*uA;
```

Use `Mat2Eul` to switch back to an Euler angle representation.

4.3 Quaternions

A quaternion is a four parameter set that embodies the concept that any set of rotations can be represented by a single axis of rotation and an angle. PSS uses the shuttle convention so that our unit quaternion (obtained with `QZero`) is [1 0 0 0]. In Figure 4.1 the axis of rotation is `[0 0 1]` (the z axis) and the angle is `theta`. Of course, the axis of rotation could also be `[0 0 -1]` and the angle `-theta`.

Quaternion transformations are implemented by the functions `QForm` and `QTForm`. `QForm` rotates a vector in the direction of the quaternion, and `QTForm` rotates it in the opposite direction. In this case

```
q  = Mat2Q(m);
uB = QForm(q,uA)
uA = QTForm(q,uB)
```

We could also get `q` by typing

```
q = Eul2Q([0;0;theta])
```

Much as you can concatenate coordinate transformation matrices, you can also multiply quaternions. If `qAToB` transforms from A to B and `qBToC` transforms from B to C then

```
qAToC = QMult(qAToB,qBToC);
```

The transpose of a quaternion is just

```
qCToA = QPose(qAToC);
```

You can extract Euler angles by

```
eAToC = Q2Eul(qAToC);
```

or matrices by

```
mAToC = Q2Mat(qAToC);
```

If we convert the three Euler angles to a quaternion

```
qIToB = Eul2Q(e);
```

`qIToB` will transform vectors represented in I to vectors represented in B. This quaternion will be the transpose of the quaternion that rotates frame B from its initial orientation to its final orientation or

```
qIToB = QPose(qBInitialToBFinal);
```

Given a vector of small angles `eSmall` that rotate from vectors from frame A to B, the transformation from A to B is

```
uB = (eye(3)-SkewSymm(eSmall))*uA;
```

where

```
SkewSymm([1;2;3])
ans =
[0 -3  2;
 3  0 -1;
-2  1  0]
```

Note that `SkewSymm(x)*y` is the same as `Cross(x,y)`.

4.4 Transformation Functions

The Aircraft Control Toolbox provides several useful functions to perform a variety of common coordinate transformations. To see a summary, type:

```
>> help ACCoord
  AC/ACCoord

  A
     AlphBeta                        - Compute angle of attack and sideslip.

  B
     BToS                            - Convert from the body axes to stability
         axes.
     BToW                            - Convert from the body frame to wind axes.

  E
     ECIToNED                        - Convert from the ECI frame to the NED
         frame.
     EulNED                          - Euler angles given ECI information.
     EulRate                         - Euler rates.
```

```
J
   JacobVB                         - Convert from the body axes to stability
       axes.

Q
   QECI                            - Compute ECI to body quaternion from ECI
       position and Euler angles.

R
   RNEH                            - Convert from the ECI frame to the NEH
       frame. This is the

S
   SToW                            - Convert from stability axes to wind axes.

V
   VBDToVBT                        - Compute the total velocity derivative from
        the body velocity and
   VTToVB                          - Compute body velocity from alpha, beta and
        vT.
```

In addition to these aircraft-specific coordinate functions, a wide range of general coordinate transformation routines are available in the Common/Coord/ directory. For example, to compute the rotation matrix from the NED frame to the BODY frame, use the `Eul2Mat.m` function.

```
>> rx = 0;                      % roll
>> ry = 0.1;                    % pitch
>> rz = pi/4;                   % yaw
>> m = Eul2Mat( [rx;ry;rz] ); % NED to BODY matrix
```

The Euler angles are the rotations about the x, y, and z axes, respectively, which correspond to roll, pitch and yaw. The matrix is computed by performing a 3-2-1 rotation sequence, where the first rotation is through the yaw angle about the 3-axis (z), then through the pitch angle about the 2-axs (y), and finally through the roll angle about the 1-axis (x).

CHAPTER 5

ENVIRONMENT

This chapter describes the functions for atmospheric properties and wind models.

5.1 Atmospheric Properties

The standard atmosphere model is stored as a lookup table in the toolbox. The values of temperature, density, pressure, speed of sound and kinematic viscosity are indexed by altitude. The data spans from sea-level to 80 km. To load the model into the workspace:

```
>> atmData = load('AtmData.txt');
```

To obtain the atmospheric properties at a desired altitude (i.e. 3000 meters), use the StdAtm.m function:

```
>> d = StdAtm( 3000, atmData, 'si' )
d =
           temperature: 268.67
              pressure: 70121
               density: 0.90926
          speedOfSound: 328.58
    kinematicViscosity: 1.8628e-05
```

The 'si' string specifies the units to be in SI system. Alternatively, you can use the English system. In this case, the altitude is entered in feet:

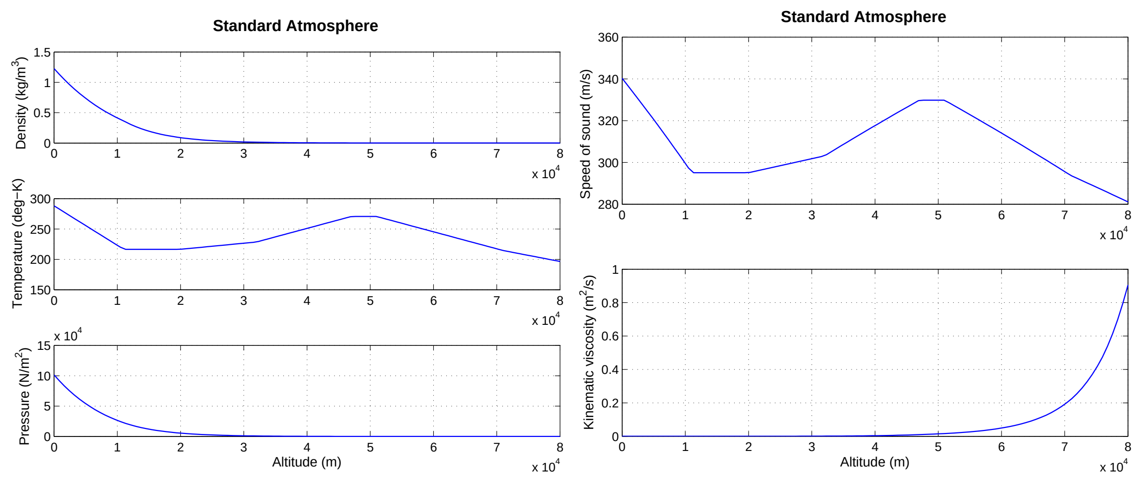
```
>> d = StdAtm( 3000/0.3048, atmData, 'eng' )
d =
           temperature: 483.606
              pressure: 1464.58050086331
               density: 0.00176421019887722
          speedOfSound: 1078.01837270341
    kinematicViscosity: 0.000200510123242469
```

The units are shown inside the StdAtm.m file.

```
% x is [altitude (m)  temperature (deg-K) pressure (N/m^2) density (kg/m^3)
%       speed of sound (m/s) kinematic viscosity (m^2/s)]
% or
%      [altitude (ft)  temperature (deg-R) pressure (lbf/ft^2) density (lbf/m^3)
%       speed of sound (ft/s) kinematic viscosity (ft^2/s)]
```

Typing StdAtm creates plots that show the variation of the properties over altitude.

Figure 5.1: Standard Atmosphere Plots



Additional atmospheric functions can be found the AC/Aero folder.

```
>> help Aero
  AC/Aero

  A
     ADC                                - Implements the "Air Data Computer" model.
     AirData                            - Computes air data based on a simplified
         standard atmosphere model. If
     AtmGamma                           - Computes the ratio of specific heats as a
         function of

  M
     MachFromPressureRatio              - Computes the Mach number from pressure
         ratio.

  P
     PressureRatioFromMach              - Computes the ratio of impact to static
         pressure from Mach number and gamma.

  R
     Reynolds                           - Compute the Reynolds number for an
         aircraft at altitude.

  S
     SimpAtm                            - Simplified atmosphere model. Agrees with
         the standard

  V
     Viscosity                          - Compute the viscosity of the air at a
         given temperature.
```

5.2 Wind Models

The toolbox provides a generic wind gust model and a steady state horizontal wind model. To see a summary of the functions:

```
>> help AeroPro
```

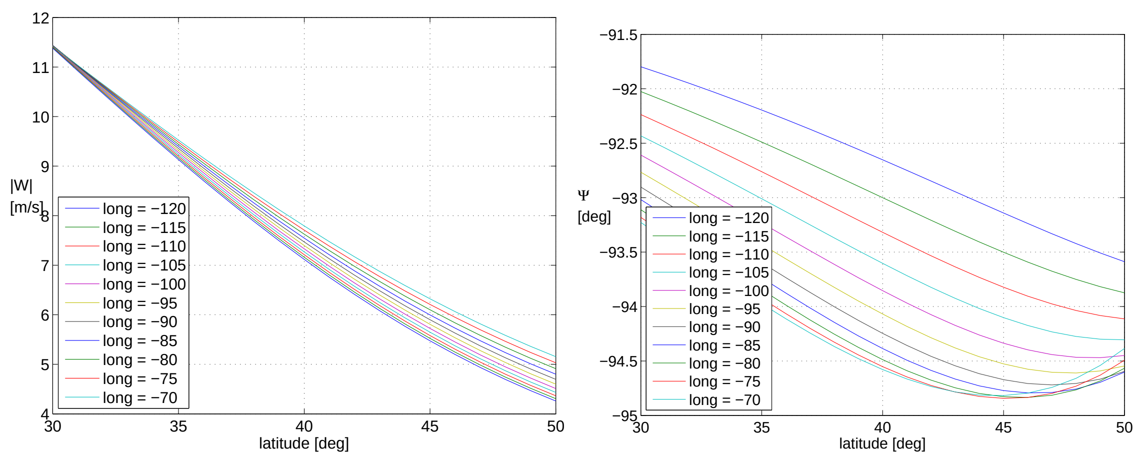
```
ACPro/AeroPro

H
   HorizontalWind                   - Form:

W
   WindGust                         - Wind gust model. Generates state space
       equations or spectral densities.
ACPro/Demos/AeroPro

G
   Gust                             - See the response of an F16 to a gust using
        a state space model.
```

The Gust demo simulates a linearized model of the F16 with randomized wind gusts. For more information view the help for the Gust and WindGust functions.

The HorizontalWind function implements the HWM93 model. This is an empirical model developed by the Naval Research Laboratory, originally written in FORTRAN. Typing HorizontalWind with no inputs runs a demo that creates a text file output. The model provides a steady-state average horizontal wind given the year, date, time of day, altitude, latitude and longitude, solar flux and magnetic index.

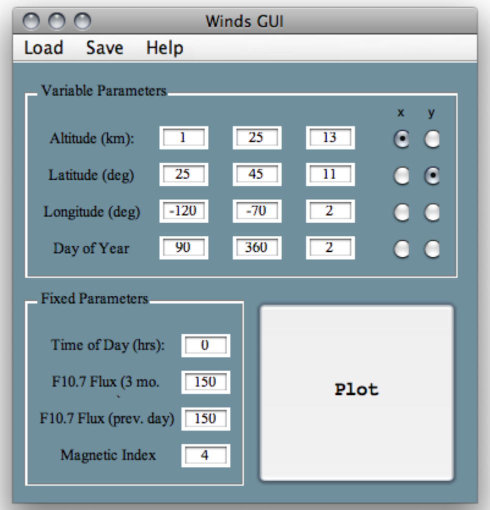
The WindLatLon function (also discussed in Chapter 11) provides a simpler interface to the horizontal wind model, taking only latitude, longitude, altitude, day of year and time of day. Plots from the built-in demo are shown below. The plots show the wind magnitude and direction at 70 thousand feet over a latitude and longitude range that covers the U.S.

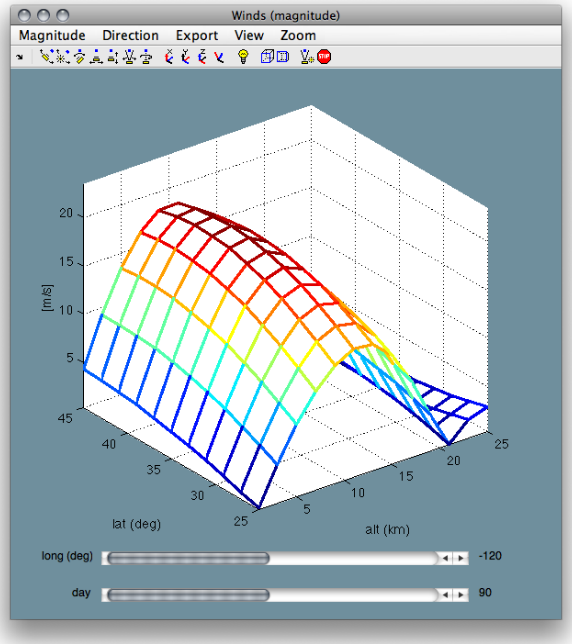
Figure 5.2: WindLatLon Demo



The WindsGUI tool provides a visual interface for the horizontal wind model. It is shown in Figure 5.3 on the following page. Use it to generate wind data over an array of different conditions, and then visualize the results with a 3D surface plot and sliders to vary additional parameters. You can also save the data that you generate to a file, and load existing files into the GUI. Once you have saved a file, you can use the WindTrendsDemo function to generate an animation of the wind behavior over a selected variable.

Figure 5.3: `WindsGUI`





CHAPTER 6

SIMULATION

6.1 Aircraft Simulations

6.1.1 Introduction

It is convenient and practical for us to differentiate between linear and nonlinear simulations. Aircraft dynamics are inherently nonlinear, and most aircraft actuators and sensors are nonlinear as well. Nonetheless, it is usually possible to linearize the dynamics and devices about some operating point where, in a sufficient restricted region around this point, the system behaves linearly. This is the basis for the linear control laws developed in this toolbox. The toolbox uses the function `AC.m` for all nonlinear aircraft simulations. The same function can also be used to develop linear models at specific operating conditions. With appropriate plug-in functions, it can perform sophisticated simulations of anything from a biplane to a single-stage-to-orbit launch vehicle.

6.1.2 Aspects of Simulation Models

Aircraft simulations can range from simple 3 DOF longitudinal dynamic models to models that incorporate the dynamics of moving parts, aero-elasticity, dynamical engine models, pilot dynamics, and so forth. There are two major tools for simulation in the toolbox. One is to use the statespace models for linear simulations. The other is to use the nonlinear simulation, `AC.m`.

Two convenient statespace simulation tools are `Step.m` and `IC.m`. They do step responses and unforced responses to an initial state, respectively. Another useful tool is `MSR.m`, which computes mean squared responses of a system to noise inputs.

The following table lists different features that simulation models can have and shows which ones are available in `AC.m`.

Table 6.1: Breakdown of Simulation Models

Feature	In AC?	Description	Uses
Rigid Body (6DOF)	Yes	3 rotational and 3 translational degrees of freedom. 6 kinematic states (7 if quaternions are used).	All aircraft
Flat Earth	Yes	Constant gravity. No Earth curvature.	Most aircraft
Ellipsoidal Earth	Yes	Includes rotation of the Earth, altitude dependent gravity, and latitude dependent Earth radius.	Launch vehicles.

Table 6.1: Simulation Models, contd.

Feature	In AC?	Description	Uses
Rotating Parts	Yes	Spinning parts, such as gas turbines or a gatling gun on an A-10.	All aircraft with engines.
Actuator Dynamics	Yes	Linear and/or nonlinear models that relate commanded thrust, deflection, etc. to the actual value. Accommodates lags, delays, limits.	All aircraft but not always necessary for preliminary designs.
Sensor Dynamics	Yes	Nonlinear models that relate measured quantity to the output measurement.	See above.
Flexible modes	Yes	Bending of wings, etc.	Important for evaluating aero-elastic effects.
Time varying inertia and mass	Yes	For launch vehicles, the inertia, CG and mass change as fuel is consumed. For lighter-than-air vehicles, the mass properties change as internal gasbags inflate and deflate with changing altitude.	Launch vehicles, lighter-than-air vehicles.
Added mass and inertia	Yes	For lighter-than-air vehicles, the added (or “apparent”) mass and inertia that must be modeled to account for momentum of the displaced fluid through which the vehicle moves.	Lighter-than-air vehicles.
Inertia and mass of moving parts	No	On some aircraft (and on boosters with large gimballed nozzle assemblies) the dynamics of moving parts can be significant.	Light aircraft and some boosters.
Detachable parts	No	Bombs and missiles.	Military aircraft.
Thermal effects	No	Interaction of heating and aerodynamics.	Supersonic aircraft. Re-entry vehicles.

Two demos show how to use `AC.m` with the `F16.m` database. The rst is `CTSim.m` which simulates a coordinated turn. The second is `Fly.m` which lets you y the F16 using the head up display, `HUD.m`. The steps you take to set up a simulation are:

1. Trim the model using `ACTrim.m`.
2. Initialize the model data structures and state vector using `ACBuild.m` and `ACInit.m`.
3. `Run AC.m`.
4. Get plot results with `ACPlot.m`.

6.1.3 Simulating Linear Systems

Creating a State Space System

If you have your model in transfer function form it can be converted to state space form using

```
[a,b,c,d] = ND2SS( num, den );
```

The variable `num` can have more than one row. To make it of type statespace

```
g = statespace( a, b, c, d );
```

If you have a nonlinear system expressed in the form and `f` is a MATLAB function in the form

```
xDot = F(x,u);
```

then

```
[a,b] = Jacobian('f',x,u);
```

Discrete-Time Systems

The simplest way to simulate a continuous time system is to discretize it using the zero order hold. This toolbox gives two ways to do this. One is the standard zero order hold

```
[aD,bD] = C2DZoh(a,b,T);
```

and the simulation is

```
x = aD*x + bD*u;
y = c*x + d*u;
```

The second is the delta form of the zero order hold

```
[aD,bD] = C2DelZoh(a,b,T);
```

and the simulation is

```
x = x + aD*x + bD*u;
y = c*x + d*u;
```

These approximations assume that the input is held constant over the interval `T`.

Time Response

The time response of a statespace system is easily obtained using ACT functions. To generate an unforced response to initial conditions, use `IC.m` The usage is:

```
[y, x] = IC( g, x0, dT, nSim )
```

where `g` is the statespace system, `x0` is the initial state, `dT` is the time step, and `nSim` is the number of points to simulate.

If you have a discrete system, `g`, you can compute the time response to a given control history as follows:

```
[x, y] = PropStateSpace( g, x0, u )
```

where `x0` is the initial state, and `u` is the control history. `u` is a $M \times N$ matrix, where M is the number of controls and N is the number of timesteps. The time between timesteps is assumed to be equal to the sampling period of the discrete system.

Alternatively, you can use the `TResp` function. This function works for either a continuous or discrete system.

```
[x,y,t,u] = TResp( g, x0, u, dT, T );
```

Here, `T` is the simulation duration and `dT` is the time interval of the simulation. The time interval should be equal to the sampling period if the system is discrete. As an option, the control vector `u` can be supplied as empty, or with just one column. If it is supplied empty, all inputs will be set to 1 for all time. If it is supplied with one column, those input values will be applied for all time.

You can use the `Step.m` function to compute the response to unit step, impulse, or white noise inputs. The usage is:

```
[y,x,t] = Step( g, iU, dT, nSim, inputType, statesFlag )
```

where `g` is the statespace system, `iU` is the index (row) of the input to use (all other inputs are set to zero), `dT` is the simulation time interval, `nSim` is the number of simulation points, `inputType` is a string for either 'step', 'impulse', or 'white noise'. This is an optional input that defaults to 'step'. The final input `statesFlag` is also optional; it is a flag to indicate whether to generate time-history plots of all the states. By default the value is 1 and the plots are made.

Frequency Response

A variety of tools are available to generate and plot the frequency response of a linear system as well. Consider a linear system, `g`. The statespace system can be created as follows:

```
>> g = statespace(a,b,c,d)
g =
        statespace object: 1-by-1
```

Similarly, the statespace data can be obtained from the system `g` as follows:

```
>> [a,b,c,d]=getabcd(g)
```

In order to generate the frequency response of the system, you may use either of the following commands:

```
>> [mag, phase, w, io] = FResp( a, b, c, d, iu, iy, w, uPhase, pType );
>> [mag, phase, w, io] = FRespG( g, iu, iy, w, uPhase, pType );
```

This is valid for a continuous time system. The magnitude is output without any scaling. To convert to decibels you must perform the `20*log10(mag)` conversion. The linear system is either described by `g` or by the statespace matrices. In each case, `iu` and `iy` are selected indices of the inputs and outputs of the system, `w` is the frequency vector, `uPhase` will cause the phase values to wrap between ±180 degrees if it is set to `'wrap'`, and `pType` is the desired type of plot, either `'bode'` or `'nichols'`. In order to generate a plot, you must call the function with no outputs.

Another function that you can use to generate frequency response data is `GSS.m`. It produces a matrix of complex data, rather than separate magnitude and phase outputs. The usage is:

```
[f,nu,w] = GSS(a,b,c,d,iu,iy,w)
```

where `a,b,c,d` are the statespace matrices, `iu` and `iy` are the selected inputs and outputs, and `w` is the frequency vector. The help information for `GSS.m` includes the following description of the output structure:

```
    For example, for 3 outputs and 2 inputs g is of the form

                     w(1)                w(2)         ...
    output 1 [ input 1 input 2 | input 1 input 2 |... ]
    output 2 [ input 1 input 2 | input 1 input 2 |... ]
    output 3 [ input 1 input 2 | input 1 input 2 |... ]
```

Use `RootLocus.m` to generate the root locus of a system. The usage is:

```
RootLocus( g, k )
```

where `g` is the continuous statespace system and `k` is an array of gains. `k` should be monotonically increasing. The closed loop poles are computed in the standard way, by applying the gain `k` to the open loop system `g` using negative feedback.

To generate a Nyquist plot, use `Nyquist.m`. Typing help on `Nyquist` shows the many forms of usage:

```
    Usage:
      [x,y] = Nyquist( g )
      [x,y] = Nyquist( g, w )
      [x,y] = Nyquist( g, w, iU, iY )
      [x,y] = Nyquist( gain, phase )
```

The inputs `g,w,iU,iY` have the same meanings as before. The inputs `gain` and `phase` can be generated directly from the `Fresp.m` function. The outputs `x` and `y` are the real and imaginary data, respectively, that is plotted on the Nyquist plot.

6.1.4 Simulating Non-Linear Systems

The toolbox provides several functions for nonlinear simulations. These functions do not vary the step size automatically or perform any error testing. One has to be careful since a large integration time step can introduce instabilities or articial damping into systems.

The Aircraft Control Toolbox also provides a variable step size routine, `RK45`, and `Euler`, a rst order method.

Given the function

```
xDot = Fun(x,t,p1,p2...p10)
```

and time step h use either

```
x = RK2( Fun , x, h, t, p1, p2, p3, p4, p5, p6, p7, p8, p9, p10 );
```

or

```
x = RK4( Fun , x, h, t, p1, p2, p3, p4, p5, p6, p7, p8, p9, p10 );
```

The variables `t` (time) and `p1` through `p10` are optional arguments. If you need more than 10 optional arguments you can pack `p1` through `p10`. For example if you need to pass two inertia matrices

```
p1 = [inertia1,inertia2];
```

6.2 Creating an Interactive Simulation

`Fly.m` is a complete, nonlinear, interactive simulation that uses all of the toolbox GUIs to allow you to y an F-16.

In this section we walk through the script `Fly.m` and explain in detail how it works. A summary of how to set up simulation scripts has already been given above so we will jump right into the details.

Listing 6.1: Main Initialization *Fly.m*

```
% Global for the time GUI
%------------------------
global simulationAction
simulationAction = '␣';

% Global for the HUD
%-------------------
global hUDOutput
hUDOutput = struct('pushbutton1',0,'pushbutton2',0,'checkbox1',0,...
                   'checkbox2',0,'checkbox3',0);

% load the F16 database
%----------------------
d = DefaultACData;

% Load the Trim State and Control Settings (found via ACTrim)
%-----------------------------------------
trimData.x = DefaultACState;
trimData    = load('F16TrimData.mat');
d.control   = trimData.control;
x           = trimData.x;

% Time
%-----
t    = 0;
dT   = 0.1;
nSim = 200/dT;

% Initialize the model
%---------------------
d    = ACInit( x, d );
```

Fly.m

In Listing 6.1, we first define the global variables for the graphical interfaces, `TimeGUI.m` and `HUD.m`. We then load the aircraft data structure, `d`, using `DefaultACData`. This returns a data structure with a standard atmosphere model and the F16 aerodynamic model. Next, the trim state and controls are loaded. The time step is then set to 0.1 sec and the number of integration steps are computed. Finally, the full simulation data structure `d` is initialized using `ACInit`. This function returns the original data structure along with new fields for generalized inertia, rotor data, flexible model data, and state names.

The `DefaultACData.m` function is shown in Listing 6.2. In the first block of code, it loads the F16 aerodynamic model data, and initializes the planet angle and angular rate (in this case we ignore planet rotation). It then specifies which functions are to be used for actuator, aerodynamic, engine, rotor, sensor and disturbance models. The name elds are names of functions that implement these different models. The files `ACAero.m`, `ACEngine.m` and `ACSensor.m` are models included with the toolbox. You can write your own models and use `AC.m` as the simulation engine, as long as you adhere to the input/output conventions for each of the functions. Type help `AC` for more information.

The middle block of code loads data for the standard atmosphere and species the units as English (ft.). The last code block initializes the controls. The actual control values can be changed at any time of course, before or during the simulation.

Listing 6.2: Default Aircraft Models and Controls *DefaultACData.m*

```
% F16 database
%-------------
d                = ACBuild('F16');
d.theta0         = 0;
d.wPlanet        = [0;0;0];
d.actuator.name = [];
d.aero.name      = 'ACAero';
d.engine.name    = 'ACEngine';
d.rotor.name     = [];
d.sensor.name    = 'ACSensor';
d.disturb.name   = [];

% Load the standard atmosphere
%----------------------------
d.atmData        = load('AtmData.txt');
d.atmUnits       = 'eng';

% Control
%--------
d.control.throttle  = .155;
d.control.elevator  = -2.5574984;
d.control.aileron   = -1.27e-6;
d.control.rudder    = 2.134e-5;
```

DefaultACData.m

The state vector loaded in using the `DefaultACState.m` function. It is specied in terms of angle-of-attack (`alpha`), sideslip (`beta`) and total velocity, `vT`. These are converted in to body state vector by `VTToVB`. The `cG`, `inertia` and `mass` are also states and are specied. The simulation uses quaternions and `QECI` converts the initial euler angles and position vector to the quaternion from ECI to the body frame. The engine model has a single state. In this case a default value is provided, but the equilibrium value can be found by using `ACEngEq`, which takes the aircraft data structure (containing the control) and nds the engine equilibrium state at that control setting. There are no actuator, sensor, ex or disturbance states so they are set to empty matrices.

Once all of the data is set the data structure of type `acstate` is created using the constructor `acstate`.

Listing 6.3: Default State Data *DefaultACState.m*

```
% default state data
%-------------------
alpha      = 0.03691;
beta       = -4e-9;
vT         = 502;
v          = VTToVB( vT, alpha, beta );
cG         = [0.35;0;0];
```

```
r          = [2.092565616797901e+07;0;0];
eulInit    = [0;0.03691;0];
qNEDToB    = Eul2Q(eulInit);
qECIToNED  = ECIToNED( r, 'quaternion' );
q          = QMult( qECIToNED, qNEDToB );
w          = [0;0;0];
wR         = 160;
mass       = 1/1.57e-3;
inertia    = [9497;55814;63100;0;-982;0];
engine     = 8.99419;
actuator   = [];
sensor     = [];
flex       = [];
disturb    = [];

% Initialize state object
%------------------------
x = acstate( r, q, w, v, wR, mass, inertia, cG, engine, actuator, sensor, flex, disturb );
```

DefaultACState.m

The trim control data for this aircraft state has been pre-computed and stored in the mat-file, `F16TrimData.mat`. Alternatively, the trim controls for a new state can be computed using the `ACTrim.m` function. Type "`help ACTrim`" for usage information.

Now we return to `Fly.m`. We have already initialized the state, models, and controls. Next, the linearized plant model is computed, just for informational purposes. The function `ACModes` extracts the standard aircraft rigid body modes. Note that `ACModes` is only valid if the aircraft is flying straight and level.

Listing 6.4: Linearized Model *Fly.m*

```
% Compute the linearized model
%-----------------------------
gLin = AC( x, 0, 0, d, 'linalpha');
aC   = get( gLin, 'a' );

% Display aircraft rigid body modes
%----------------------------------
ACModes( gLin );
```

Fly.m

Next the two main graphical interfaces are initialized: the heads up display (HUD) and the 3D CAD model window. These displays are discussed more in Section 6.4 on page 38. The settings for maximum controls are used to convert mouse movement into control values.

Listing 6.5: Setting up the HUD and 3D Aircraft Display *Fly.m*

```
% Set up the HUD
%---------------
dHUD.atmData     = d.atmData ;
dHUD.atmUnits    = 'eng';

cHUD.control     = d.control;
cHUD.elevatorMax = 90;
cHUD.aileronMax  = 90;
cHUD.rudderMax   = 90;
cHUD.dT          = dT;
hHUD = HUD( 'init', dHUD, x, [], cHUD );

% Set up the aircraft display
%----------------------------
gF16 = load( 'gF16' )
hF16 = DrawAC( 'init', gF16, x, [], d.atmUnits  );
```

Fly.m

Plotting is initialized by specifying the names of plots. `ACPlot.m` lists all available plots. The time display is discussed in the graphics section.

Listing 6.6: Initializing `ACPlot.m` *Fly.m*

```
% Initialize the plots
%---------------------
plots = [ 'Euler angles       ';...
          'Quaternion         ';...
          'Quaternion NED To B';...
          'Angular rate       ';...
          'Position ECI       ';...
          'Velocity           ';...
          'Alpha              ';...
          'Rudder             ';...
          'Throttle           ';...
          'Aileron            ';...
          'Elevator           '];
dPlot = ACPlot( x, 'init', plots, d, 200, dT, nSim );
```

Fly.m

Listing 6.7: Initializing the Time Display *Fly.m*

```
% Initialize the time display
%----------------------------
tToGoMem.lastJD        = 0;
tToGoMem.lastStepsDone = 0;
tToGoMem.kAve          = 0;
ratioRealTime          = 0;
[ ratioRealTime, tToGoMem ] =  TimeGUI( nSim, 0, tToGoMem, 0, dT, 'F16 Simulation' );
```

Fly.m

This completes the initialization steps. Next comes the simulation loop.

The rst section of the simulation loop updates the time display periodically. The next sections update the HUD and extract the control settings. Plot data storage is done next. The 3D display is updated and then the simulation state is updated.

Listing 6.8: Simulation Loop *Fly.m*

```
% Simulation Loop
%----------------
for k = 1:nSim

  % Display the status message
  %---------------------------
  [ ratioRealTime, tToGoMem ] = TimeGUI( nSim, k, tToGoMem, ratioRealTime, dT );

  % HUD information
  %----------------
  hHUD = HUD( 'run', dHUD, x, hHUD, cHUD );

  % Controls
  %---------
  d.control  = hHUD.control;

  % Plotting
  %---------
  dPlot = ACPlot( x, 'store', dPlot, d.control );

  % 3D Display
  %-----------
  hF16 = DrawAC( 'run', gF16, x, hF16, d.atmUnits );

  % The simulation
  %---------------
  x     = AC( x, t, dT, d );
  t     = t + dT;
```

Fly.m

The listing below shows the end of the simulation loop. This code implements commands from `TimeGUI.m`.

Listing 6.9: Time Control in Simulation Loop *Fly.m*

```
  % Time control
  %-------------
  switch simulationAction
    case 'pause'
      pause
      simulationAction = '␣';
    case 'stop'
      return;
    case 'plot'
      break;
  end
  HUDCntrl;
end
```

Fly.m

Finally, we close the time GUI and create the plots of states, controls, and outputs using `ACPlot.m`.

Listing 6.10: Plot Generation at end of Simulation *Fly.m*

```
TimeGUI('close');

% Create the plots
%-----------------
ACPlot( x, 'plot', dPlot );
```

Fly.m

6.3 Customizing a Simulation

You can add sensor, actuator and ex dynamics to the simulation by plugging in your own routines. For example, the script `CResponse.m` shows the aircraft response to a variety of control inputs. The script `CActuator.m` is the same script but with rst order actuator dynamics added. Two things are needed to add actuator dynamics. The rst is a few changes to CResponse.m shown in Listing 6.11. The rst line creates a data structure for the data needed by the actuator model. In this case, the actuators are modeled as rst order lags. The first member of the structure is the name of the function that models the actuator. The last three members are the break frequencies for each actuator model. The second line initializes the actuator state to the current value of the controls.

Listing 6.11: Adding Actuatator Dynamics

```
d.actuator = struct('name','F16Act','aileron',2,'elevator',2,'rudder',2);
actuator   = [d.control.elevator;d.control.aileron;d.control.rudder];
```

The next part is the actuator model shown in Listing 6.12. The variable `x` is the actuator part of the state vector, initialized above. The variable `controlInput` is the control data structure, used to initialize the actu- ator state vector above, and `actuatorData` is the actuator data structure, `d.actuator`.

Listing 6.12: The actuator model

```
function [dX, control] = F16Act( x, controlInput, actuatorData )
control.throttle = controlInput.throttle;
control.elevator = x(1);
control.aileron  = x(2);
control.rudder   = x(3);
dX     = zeros(3,1);
dX(1) = actuatorData.elevator*(controlInput.elevator - x(1));
```

```
dX(2) = actuatorData.aileron *(controlInput.aileron  - x(2));
dX(3) = actuatorData.rudder  *(controlInput.rudder   - x(3));
```

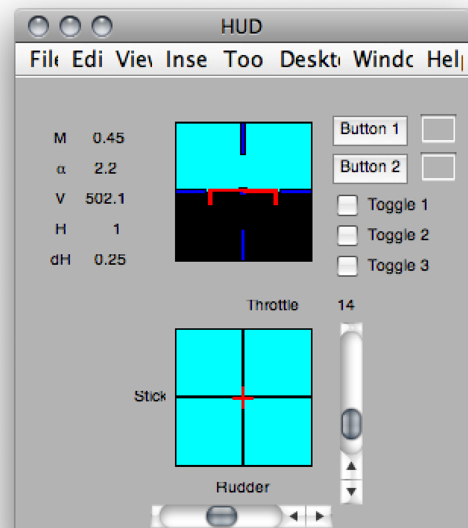
6.4 Simulation Graphics

6.4.1 Simulation GUI's

The toolbox has three GUI windows that you can use in your simulations. Each GUI has an initialization function call format and a run-time function call format. The three GUIs are shown in the following figures.

The first is `HUD.m` a "Head-Up Display" that allows you to control your aircraft model. It can be used with any simulation. It has an airplane mode and a helicopter mode. You move the sliders for pedal and throttle and move the box in the lower display by clicking on the new desired location. For an airplane this causes the ailerons or elevators to move. The numerical displays on the left are Mach number, angle of attack in degrees, velocity, altitude and altitude rate. The two push buttons and three checkboxes can be assigned names and functions by the user.

Figure 6.1: Heads-Up Display, HUD



The second is `TimeGUI.m` which lists time statistics and allows you to control your simulation. By pushing one of the three buttons you can stop the simulation, pause, or exit the simulation loop. If you use one of the toolbox plotting routines, exiting will cause all existing data to plot.

The last is the aircraft display, DrawAC.m which gives you a 3-dimensional picture of what your aircraft is doing. Any aircraft model can be loaded into the display. The toolbox supplies a preprocessed F-16 model as an example.

The demo `Fly.m`, described in detail in the previous sections of this chapter, provides a useful reference for how to use all three graphical interfaces.

Figure 6.2: Time Information Window, `TimeGUI`

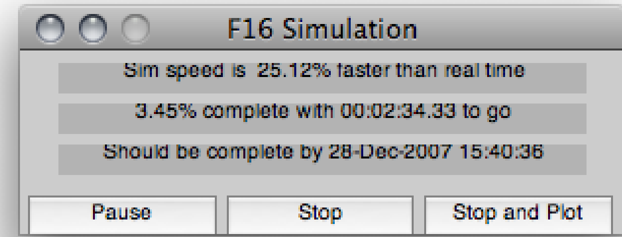
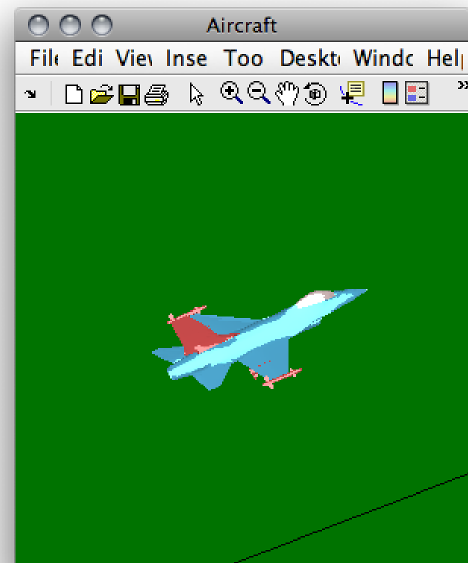


Figure 6.3: 3D Aircraft Display



6.4.2 Post-Simulation Plotting

The toolbox has two plotting functions, `ACPlot.m` and `StateSpacePlot.m`. The former is for use with the `acstate` class and the latter with the statespace data class. The usage of `ACPlot.m` in the script `Fly.m` shows how to use that function. The initialization of the plot names and plotting data structure is shown in Listing 6.6 on page 36. Subsequent storage of data to be plotted is done inside the simulation loop, as follows:

```
dPlot = ACPlot( x, 'store', dPlot, d.control );
```

where `x` is the state vector (type `acstate`) at the current time step, and `d.control` contains the current control data.

To see a list of the plots that can be generated, type:

```
ACPlot( x, 'info' )
```

To generate a set of plots, type:

```
ACPlot( x, 'plot', dPlot )
```

The plotting function `StateSpacePlot` is similar, but it is used slightly differently. It allows you to distinguish between states, controls, and outputs, and produces plots accordingly. An example can be found in `OH6ASim.m`.

CHAPTER 7

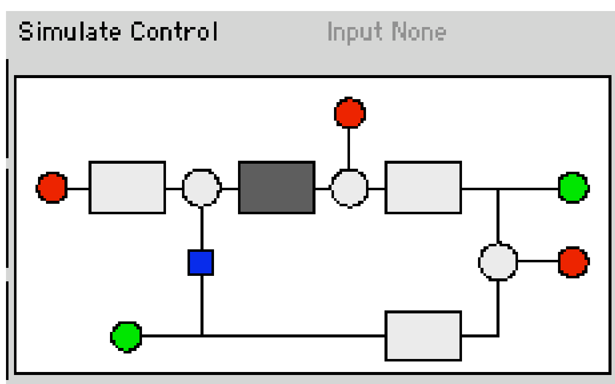
DESIGNING CONTROLLERS

This chapter shows how to design controllers using the ControlDesignPlugIn. The three major methodologies are discussed, Linear Quadratic, Eigenstructure assignment and Single-Input-Single-Output. This section focuses on how to use the Control Designer GUI.

7.1 Using the block diagram

The block diagram from the control designer GUI is shown in the following figure.

Figure 7.1: Block diagram



When you select a block, all operations (including all of the simulation buttons, loading and saving, apply only to that block. To work with the entire diagram click the highlighted block so that none are highlighted. The blue box opens and closes the control loops. When it is blue (the default) the system is closed. To open the loops, click the box.

The red circles are inputs and the green are outputs. When you are working with the entire system you can select the input and output points by clicking on the red and green circles. The red circle on the left is the command input, the one on the top is the disturbance input and the one on the right is the noise input. The green output on the right is the state output and the green output on the left is the measurement output.

7.2 Linear Quadratic Control

In this example we will design a compensator for a double integrator using full-state feedback. A double integrator's states are position and velocity. For full-state feedback, both must be available.

This example is automated using `LQFullState.m`.

Listing 7.1: Listing

```
a         = [0 1;0 0];
b         = [0;1];
c         = eye(2);
d         = [0;0];

g         = statespace( a, b, c, d, 'Double␣Integrator',...
            {'position', 'velocity'}, 'force', {'position', 'velocity'} );

save( 'DoubleIntegrator', 'g' );

q         = eye(2);
r         = 1;

w.q       = q;
w.r       = r;

gC        = LQC( g, w, 'lq' );
k         = get( gC, 'd' );

[a,b,c,d] = getabcd( g );
inputs    = get( g, 'inputs' );
inputs    = strvcat( inputs, 'pitch␣rate' );
g         = set( g, a - b*k*c, 'a' );
Step( g, 1, 0.1, 100 );
```

The script sets values for the controller design matrices. As you can see, you can also use `LQC.m` outside of the design GUI. This script also creates the plant model, `DoubleIntegrator.mat`. Run the script and you will get the plot in Figure 7.2 on the next page.

Now type `ControlDesignPlugin`. Select the plant and load in `DoubleIntegrator.mat`. Select the control and then select the LQ tab. Select full state feedback. Enter q and r into the corresponding input fields. The display will look as follows (Figure 7.3 on the facing page). Push Create. The values for q and r are read in from the workspace. This eliminates the need to type in potentially large matrices. When you read in a controller these matrices are stored in the workspace.

Next click the control block so that you get the whole system. It will unhighlight. You can now do a step response by pushing step Figure 7.4 on page 44.

7.3 Single-Input-Single-Output

Close and reopen the GUI and load in the double integrator plant. Next select the control block and the SISO tab. Add the input position and output force. Then add a transfer function TF. Push the button to make position the transfer function input and force the output. Now select TF and click PD in the SISOList. The GUI will look like that in Figure 7.5 on page 44.

Hit the Save button under the transfer function heading. Select the MapIO tab. You will see that the inputs and outputs of the plant and controller are aligned properly.

Figure 7.2: Step response

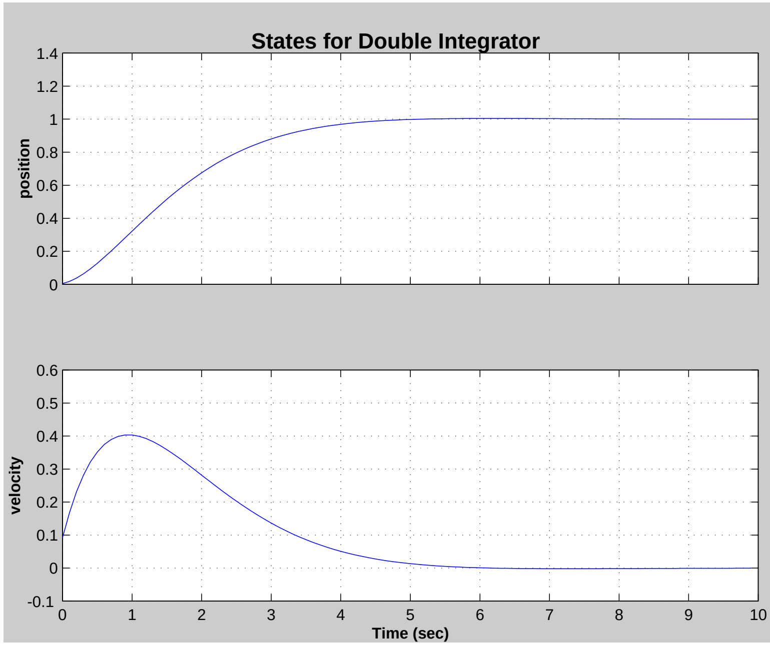


Figure 7.3: LQ GUI

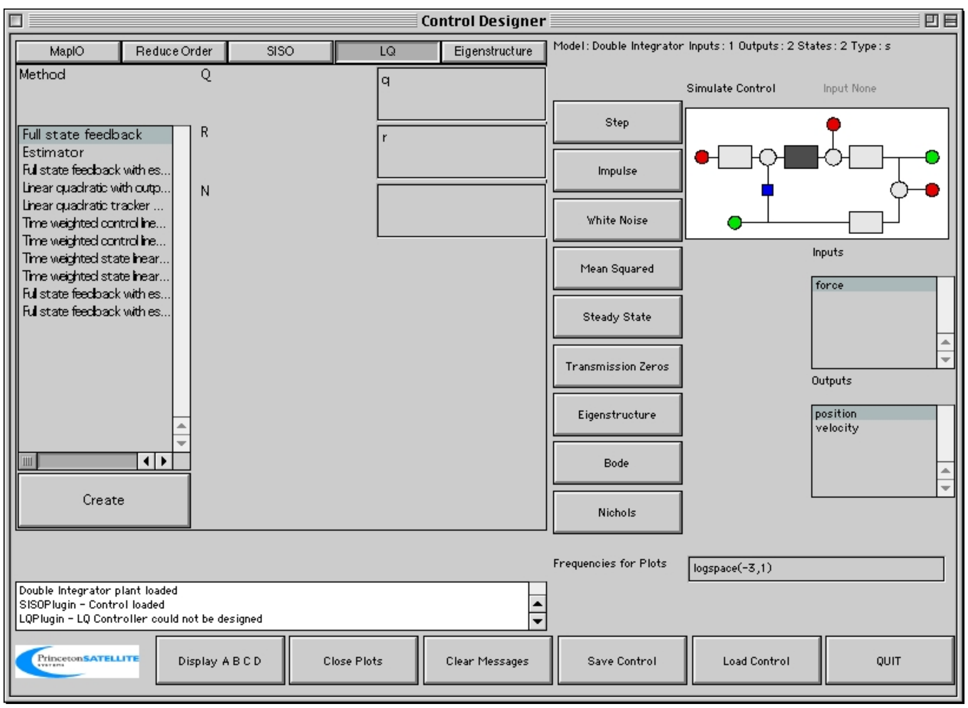


Figure 7.4: Step response from the GUI

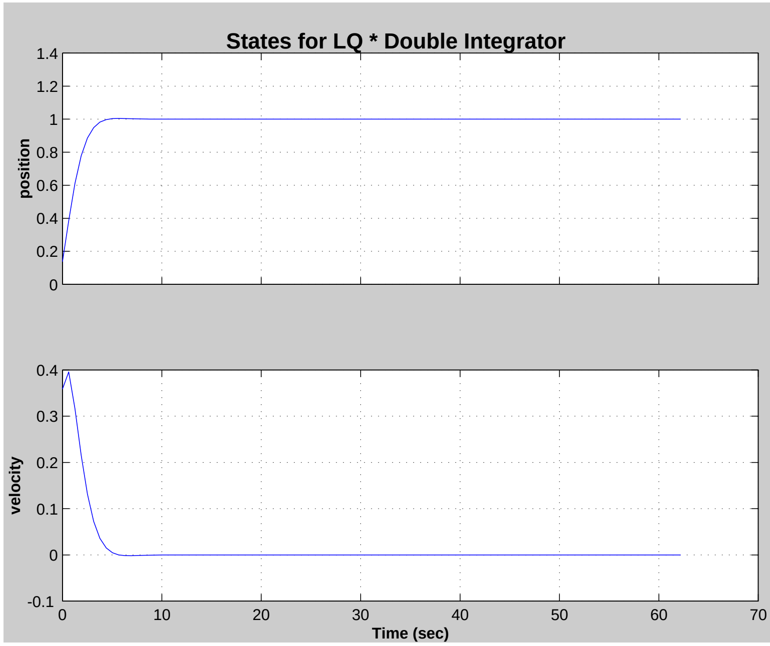


Figure 7.5: SISO inputs

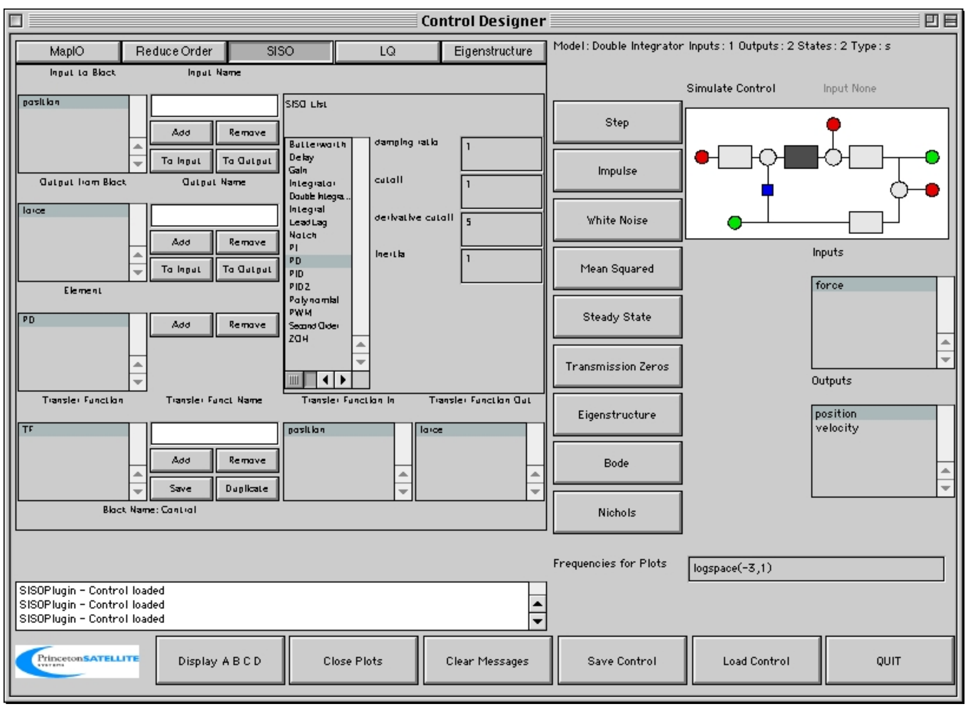
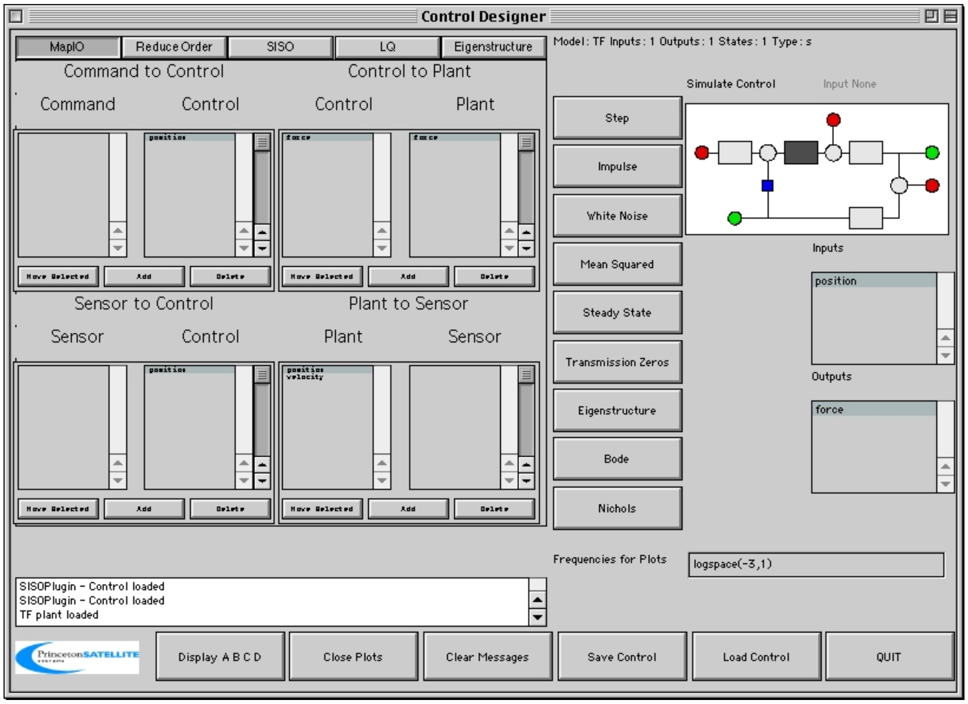
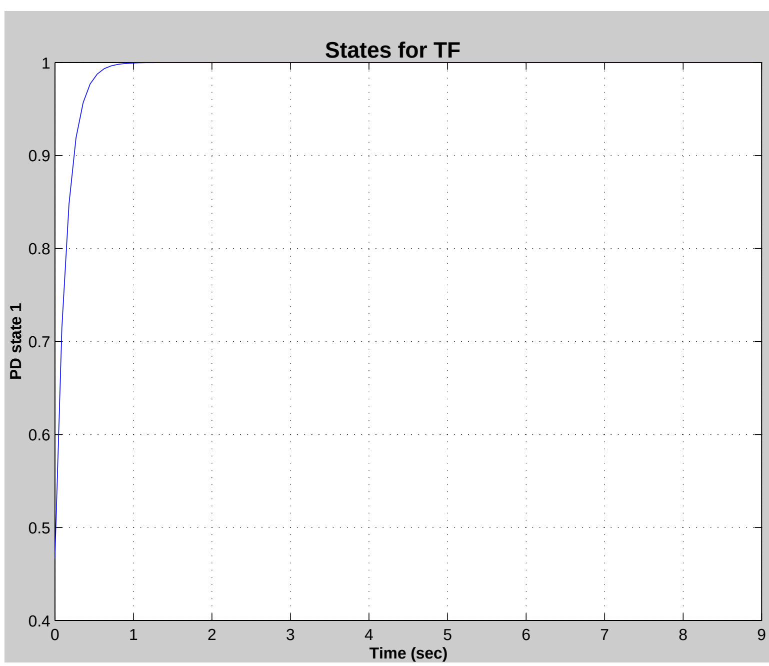


Figure 7.6: MapIO



Under plant to sensor click velocity and hit remove since it is not used by the SISO controller. When removed, velocity is prefixed by a star to indicate that it is part of the plant buy unused. Click the control box to select the whole plant and hit step. You will see the following step response (Figure 7.7).

Figure 7.7: SISO step response



7.4 Eigenstructure Assignment

Run the script CCVDemo. This script generates the inputs for the eigenstructure assignment example. The model is already stored in CCVModel.mat.

Listing 7.2: CCVDemo

```
% Plant matrix
%-------------
g = CCVModel;

% Desired eigenvalues and eigenvectors
%-------------------------------------
lambda = [ -5.6 + j*4.2; -5.6 - j*4.2; -1.0;...
           -19.0; -19.5];
vD = [ 1-j  1+j  0  1  1;...
      -1+j -1-j  1  0  0;...
       0    0    0  0  0];

% We really want to decouple gamma
%---------------------------------
w  = [ 1    1    1  1  1;...
       1    1    1  1  1;...
       100  100  1  1  1];

% The design matrix.
%-----------------------------------------
d  = [eye(3),zeros(3,2);... % Desired structure for eigenvector 1
      eye(3),zeros(3,2);... % Desired structure for eigenvector 2
      0 1 0 0 0;...         % Desired structure for eigenvector 3
      0 0 1 0 0;...         %
      0 0 0 1 0;...         % Desired structure for eigenvector 4
      0 0 0 0 1];           % Desired structure for eigenvector 5

% Rows in d per eigenvalue
% Each column is for one eigenvalue
% i.e. column one means that the first three rows of
% d relate to eigenvalue 1
%---------------------------------------------------
rD = [3,3,2,1,1];

% Compute the gain and the achieved eigenvectors
%-----------------------------------------------
[k, v] = EVAssgnC( g, lambda, vD, d, rD, w );
```

lambda gives the desired eigenvalues, something that would be specified for simple pole placement. vD are the desired eigenvectors which we can assign because we are using multi-input-multi-output control. The weighting matrix shows how important each element of the desired eigenvector is to the control design. Notice that the length of each eigenvector in vD is not the length of the state. This is because we don't care about most of the eigenvector values. The matrix d is used to related the desired eigenvector matrix to the actual states. rD indexes the rows in d to the eigenvalues. One column per state. Each row relates vD to the plant matrix For example, rows 7 and 8 relate column 3 in vD to the plant. In this case vD(1,3) relates to state 2 and vD(2,4) relates to state 3.

Now open ControlDesignPlugin. Click on the plan box and load CCVModel.mat. Now click on the Eigenstructure tab and enter lambda, vD, d, rD and w into the corresponding spots. The GUI will look as shown in Figure 7.8 on the facing page.

Push Create. Next push Step. You will see the plot in Figure 7.9 on the next page.

Figure 7.8: Eigenstructure design GUI

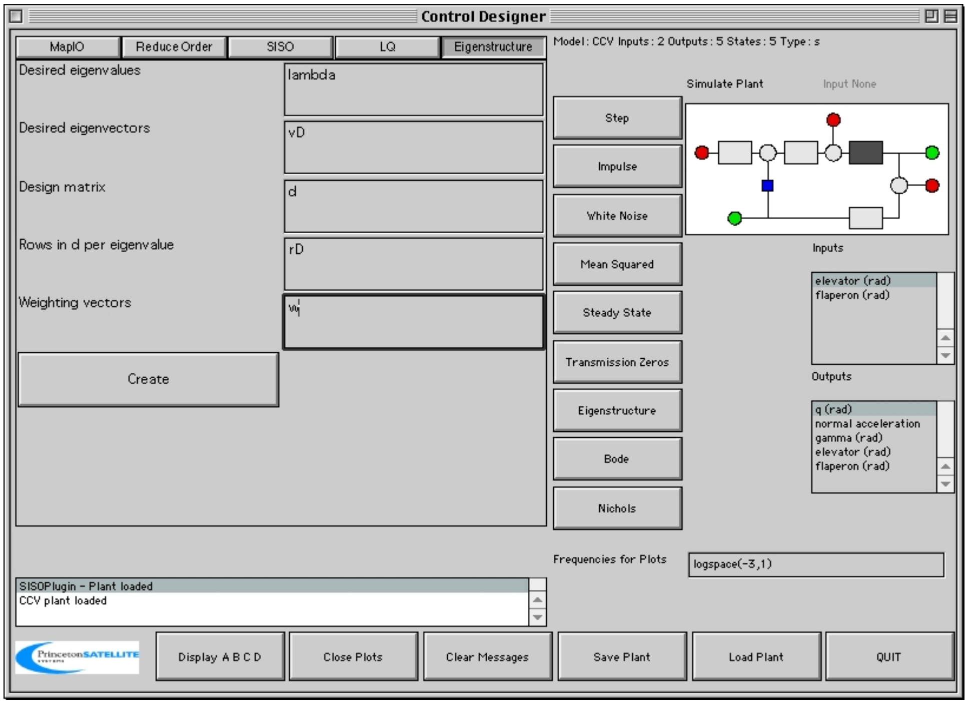
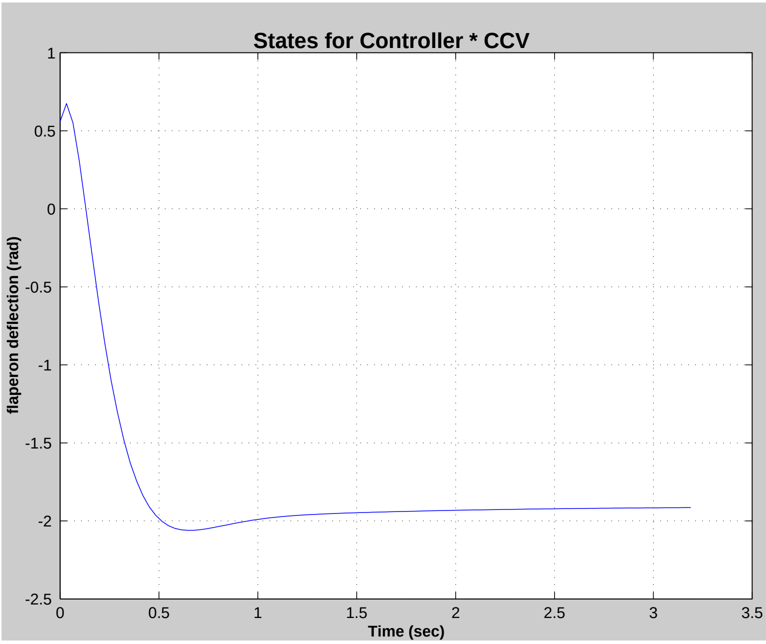


Figure 7.9: Step response with eigenstructure assignment



CHAPTER 8

IMPLEMENTING CONTROLLERS

This chapter shows how to design implement controllers in the nonlinear simulation.

8.1 A General Interface

The function `AircraftControl.m` provides a general interface that can be used to structure your control system. The following listing shows the entry point for `AircraftControl.m`.

Listing 8.1: Top of Function *AircraftControl.m*

```
function y = AircraftControl( action, d )

persistent s

switch action
  case 'initialize'
     s = Initialize( d );
  case 'update'
     [y,s] = Update( s, d );
end
```

_ *AircraftControl.m* Here, `s` is used for global memory. Notice that `s` is always returned from the internal functions. `d` is passed to the function to initialize it. `y` is the output of the controller and `s` is the updated memory.

This version of `AircraftControl` just sends commands open loop to the aircraft. The initialization function is shown below.

Listing 8.2: Initialization Function `AircraftControl.m`

```
function s = Initialize( d )

s.actuatorName = d.actuatorName;
s.control      = d.control;

switch d.actuatorName
        case 'elevator'
                s.cDS.dT        = 0.5;
                s.cDS.magnitude = 2;
                s.cDS.init      = d.control.elevator;

        case 'throttle'
                s.cDS.dT        = 3;
        s.cDS.magnitude = 0.1;
                s.cDS.init      = d.control.throttle;
```

```
        case 'aileron'
                s.cDS.dT        = 2;
        s.cDS.magnitude = 5;
                cDS.init        = d.control.aileron;

        case 'rudder'
                s.cDS.dT        = 0.5;
                s.cDS.magnitude = 2;
                s.cDS.init      = d.control.rudder;

        otherwise
                error([d.actuatorName 'is␣not␣available'])
end
```

AircraftControl.m

The names of the actuator to be used is being passed to this routine. Details for the actuation of the actuator are given in each case statement.

The update function is called each time step and is shown below.

Listing 8.3: Update Function AircraftControl.m

```
function [y, s] = Update( s, d )

% This is just to test the actuators
%-----------------------------------
switch s.actuatorName
        case 'elevator'
                        s.control.elevator  = CInputs( d.t, 1, s.cDS, 'doublet' );
        case 'throttle'
                        s.control.throttle  = CInputs( d.t, 1, s.cDS, 'doublet' );
        case 'aileron'
                        s.control.aileron   = CInputs( d.t, 1, s.cDS, 'doublet' );
        case 'rudder'
                        s.control.rudder    = CInputs( d.t, 1, s.cDS, 'doublet' );
end

y = s.control;
```

AircraftControl.m

The data structure `s.cDS` is passed to `CInputs.m` which generates the control signature. The output is the data structure `s.control`. This function is shown as implemented in the `ACControl.m` demo. The following listing shows relevant excerpts from that script.

Listing 8.4: Portions of Function with Control Data Structure ACControl.m

```
% Control
%--------
d.control.throttle  =   0.1485;
d.control.elevator  =  -1.931;
d.control.aileron   =  -7e-8;
d.control.rudder    =   8.3e-7;

...

% Set up the control inputs
%--------------------------
AircraftControl( 'initialize', struct( 'actuatorName', actuatorName, 'control', d.control) )

...

for k = 1:nSim

  % Controls
  %---------
  d.control = AircraftControl( 'update', struct( 't', t, 'sensor', ACSensor(x,d,'meas') ));
```

ACControl.m

8.2 Closed-Loop Control

8.2.1 Introduction

The function `AircraftControl.m` can be easily modied to do closed loop control. This example is based on [Ref. C-1] Example 4.5-1, a pitch rate control augmentation system. Note that in the reference the authors implement the pitch augmentation system as an analog system.

There are four parts to this problem:

- Sensor input
- Actuator Model
- Control law
- Pilot input
- Control implementation

In this case we are using the elevator as the actuator. Our inputs are the pitch rate and angle of attack.

Our new control function is called `AircraftControlCAS.m`. The demo is `F16CAS.m`. The control design script is `CASDesign.m`.

8.2.2 Sensor Input

The sensors are available from the function `ACSensor.m`. You will use sensor outputs 5, alpha or angle-of-attack, and 3, q or pitch rate. This sensor model does not include any dynamics.

8.2.3 Actuator Model

The new actuator model is in `F16Actuator.m` shown in the following listing. Each actuator is modeled as a simple lag. `dX` is the derivative vector and the control output is now the state `x` which is the ltered control input.

Listing 8.5: The F16 Actuator Function *F16Actuator.m*

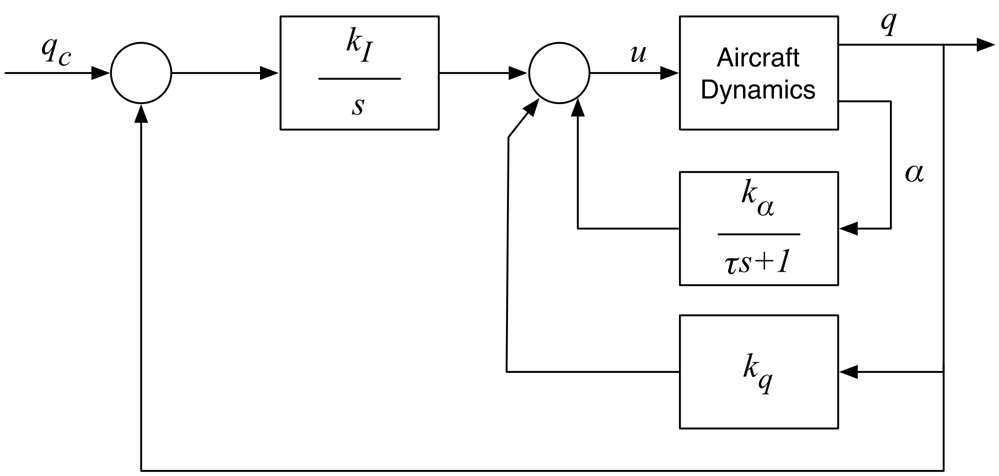
```
function [dX, control] = F16Actuator( x, control, d )
dX = [...
      (control.throttle - x(1))/d.throttleLag;...
      (control.elevator - x(2))/d.elevatorLag;...
      (control.aileron  - x(3))/d.aileronLag;...
      (control.rudder   - x(4))/d.rudderLag];

control.throttle = x(1);
control.elevator = x(2);
control.aileron  = x(3);
control.rudder   = x(4);
```

F16Actuator.m

8.2.4 Control Law

The controller, consisting of a integrator outer loop and two proportional inner loops is shown in the following block diagram. Notice that the error between the command the measured pitch rate is integrated while the pitch rate, and not the pitch rate error, is fed back through a proportional loop. The measured pitch rate is subtracted from the

Figure 8.1: Pitch Axis Control Augmentation System



commanded pitch rate and integrated in the outer loop. The inner loop consists of two loops, an alpha and a pitch rate loop. The control law is:

$$u = -\left(\frac{k_I}{s}(q_c - q) + k_q + \frac{k_\alpha}{\tau s + 1}\alpha\right) \tag{8.1}$$

This controller is demonstrated in the script CASDesign.m. The F-16 model is augmented with elevator dynamics represented by a simple lag. When designing you need to

- set up the model
- set the initial state
- set the initial settings of the actuators
- linearize the model
- do your control design
- simulate

The script `CASDesign.m` does these things. The control design part is limited to using the gains from the reference. The script does a state-space simulation of the controller and the dynamics as a nal check on the response.

The first three steps are the same in the design scripts and the simulation scripts. The simulation scripts also usually linearize the model to extract the aircraft modes.

Setting up the model is shown in the following listing.

Listing 8.6: Setting up the model *CASDesign.m*

```
% F16 database
%-------------
```

```
d               = ACBuild('F16');
d.theta0        = 0;
d.wPlanet       = [0;0;0];
d.actuator.name = 'F16Actuator';
d.aero.name     = 'ACAero';
d.engine.name   = 'ACEngine';
d.rotor.name    = [];
d.sensor.name   = 'ACSensor';
d.disturb.name  = [];
% Load the standard atmosphere
%-----------------------------
d.atmData       = load('AtmData');
d.atmUnits      = 'eng';

% Actuator dynamics
%------------------
d.actuator.throttleLag = 4.9505e-02;
d.actuator.elevatorLag = 4.9505e-02;
d.actuator.aileronLag  = 4.9505e-02;
d.actuator.rudderLag   = 4.9505e-02;
```

CASDesign.m

The data structure entries with the `.name` fields are the names of the plugin functions, such as the `F16Actuator` described above. If there is no plugin you enter `[]`. The initial state is loaded as shown in the following listing.

Listing 8.7: Initializing the State CASDesign.m

```
% Control settings
%-----------------
d.control.throttle  =   0.1385;
d.control.elevator  =  -0.7588;
d.control.aileron   =  -1.2e-7;
d.control.rudder    =   6.2e-7;

% Initial state vector Corresponding to Nominal in
% Table 3.4-3 p. 139 of the reference
%-------------------------------------------------
altitude  = 100;
alpha     = 0.03691;
beta      = -4.0e-9;
theta     = 0.03991;
vT        = 502;
v         = VTToVB( vT, alpha, beta );

cG        = [0.35;0;0];

r         = [2.092565616797901e+07+altitude;0;0];

eulInit   = [0;theta;0.00];

q         = QECI( r, eulInit );
w         = [0;0;0];

wR        = 160;
engine    = ACEngEq( d, v, r ); % Engine state
mass      = 1/1.57e-3;
inertia   = [9497;55814;63100;0;-982;0];
actuator  = [0;0;0;0];
sensor    = [];
flex      = [];
disturb   = [];

% Initial time and state
%-----------------------
x = acstate( r, q, w, v, wR, mass, inertia, cG, engine, actuator, sensor, flex, disturb );
```

CASDesign.m

We only want to work with the longitudinal dynamics for `q` and `alpha`. Extracting those state space matrices is shown in the following listing.

Listing 8.8: Extracting Longitudinal Dynamics *CASDesign.m*

```
% Generate the state space model
%-------------------------------
stateName.actuator = {'Throttle␣Lag', 'Elevator␣Lag', 'Aileron␣Lag', 'Rudder␣Lag'};
d                  = ACInit( x, d, stateName );
g                  = AC( x, 0, 0, d, 'linalpha');
aC                 = get( g, 'a' );
cC                 = get( g, 'c' );
bC                 = get( g, 'b' );

kLon         = [10 11 5 8 26];
kLonAQ       = [11 8 26];
kAlphaSensor = 5;
kQSensor     = 3;
kElevator    = 2;

disp('The␣state␣space␣matrices␣for␣just␣alpha␣and␣q')
a    = aC(kLonAQ,kLonAQ)
b    = bC(kLonAQ,kElevator);
c    = cC(kAlphaSensor,kLonAQ); % alpha only

disp('The␣plant␣eigenvalues')
eig(a)
```

CASDesign.m

The printed results of the state space matrices and plant eigenvalues are shown below.

```
The state space matrices for just alpha and q
a =
         -1.01671203478116         0.905172891717086       -0.0022528435863352
         -1.20309885574413            -1.26467603375                -0.1800126
                         0                         0               -20.1999798
The plant eigenvalues
ans =
          -1.14069403426558 +      1.03616646060335i
          -1.14069403426558 -      1.03616646060335i
                -20.1999798
```

Next, the script constructs a closed-loop system. It first constructs the inner loop by applying a first order integral feedback controller for `alpha`. It then constructs the outer loop by feeding back both `alpha` and `q` to perform pitch rate tracking.

Listing 8.9: Constructing Closed-Loop System *CASDesign.m*

```
% First design the inner loop
%----------------------------
kAlpha   =  -0.08; % Notice this sign!
tauAlpha =   0.1;
aAlpha   =  -1/tauAlpha;
bAlpha   =   1/tauAlpha;
cAlpha   =   kAlpha;
dAlpha   =   0;

% Test it in continuous mode
%---------------------------
aCL = CLoopS( a, b, c, aAlpha, bAlpha, cAlpha, dAlpha ); % This applies negative feedback

disp('Closed␣loop␣eigenvalues␣for␣the␣inner␣loop')
eig(aCL)

% Now add the outer loop
%-----------------------
```

```
c    = cC([kAlphaSensor kQSensor],kLonAQ);
kI   =  1.5;
kQ   =  -0.5;
aCAS = [-1/tauAlpha 0;0 0];
bCAS = [1/tauAlpha 0;0 -1];
cCAS = [kAlpha kI];
dCAS = [0 kQ];

% Test it in continuous mode
%----------------------------
aCL = CLoopS( a, b, c, aCAS, bCAS, cCAS, dCAS ); % This applies negative feedback

disp('Closed␣loop␣eigenvalues␣for␣the␣inner␣and␣outer␣loops')
eig(aCL)
```

CASDesign.m

The script does not actually perform a design, it simply uses the gains provided in the reference and checkes the eigenvalues. The printed results of the eigenvalues of the inner and outer loops are:

```
Closed loop eigenvalues for the inner loop
ans =
          -20.1698093439904
          -10.1598957054063
           -1.0758314095672 +      1.39018853926588i
           -1.0758314095672 -      1.39018853926588i
Closed loop eigenvalues for the inner and outer loops
ans =
          -13.2616892668476
          -10.8793554469357
          -0.85305233171349
          -3.74363541151719 +      3.37917509890488i
          -3.74363541151719 -      3.37917509890488i
```

Finally, the discrete-time system is simulated from zero initial conditions to track a step input of the pitch rae signal. The statespace simulation code is shown below.

Listing 8.10: Constructing Closed-Loop System CASDesign.m

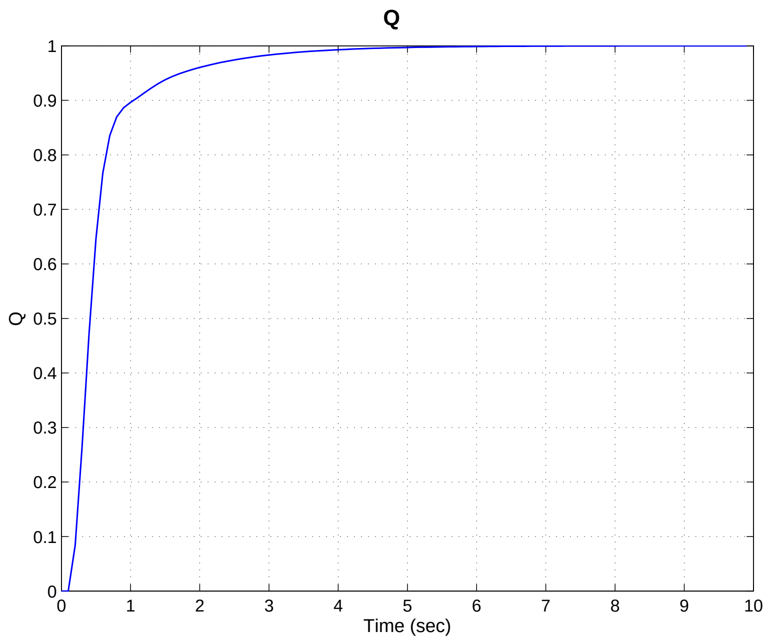
```
dT           = 0.1; % 10 Hz controller works well

[a, b]       = C2DZOH( a, b,       dT );
[aCAS, bCAS] = C2DZOH( aCAS, bCAS, dT );

nSim         = 100;

xPlot        = zeros(1,nSim);

qC           = 1.0;
xCAS         = [0;0];
x            = [0;0;0];
y            = [0;0];

for k = 1:nSim

  xPlot(k) = y(2);

  y    = c*x;

  xCAS = aCAS*xCAS + bCAS*[y(1);y(2) - qC];
  yCAS = -(cCAS*xCAS + dCAS*y);

  x    = a*x + b*yCAS;

end

t = (0:(nSim-1))*dT;
```

```
Plot2D( t, xPlot, 'Time␣(sec)', 'Q' );
```

CASDesign.m

The plot produced from the simulation is shown in Figure 8.2.

Figure 8.2: Pitch Rate Tracking Step Response



8.3 Pilot Input

Pilot input can be done in two ways. One is just to pass the desired input into your control function. The second is to customize the HUD. In this example, we need a pitch rate input which is not an available output on the standard HUD. We would like the pilot to be able to select a pitch rate and then command the aircraft. As an illustrative example, the pilot input can be read in using the following code, which is used in the `F16CAS` demo.

Listing 8.11: Initializing the controller gains in F16CAS F16CAS.m

```
% Pitch rate input
%-----------------
pilotPitchRateInput = struct( 'enter', hUDOutput.pushbutton1, 'value', hHUD.control.text1 );

% Controls
%---------
d.control = AircraftControlCAS( 'update', struct( 't', t, 'sensor', ACSensor( x, d, 'meas' ),
     'pilotPitchRateInput', pilotPitchRateInput ) );
```

F16CAS.m

8.4 Control Implementation

The controller described above is implemented in `AircraftControlCAS`. As with the previous example there are two parts, the initialization and the update. The initialization is shown in the following listing.

Listing 8.12: Initializing the controller gains *AircraftControlCAS.m*

```
function s = Initialize( d )

kI        =   1.5;
kQ        =  -0.5;
kAlpha    =  -0.08; % Notice this sign!
tauAlpha =   0.1;
s.aCAS    =   [-1/tauAlpha 0;0 0];
s.bCAS    =   [1/tauAlpha 0;0 -1];
s.cCAS    =   [kAlpha kI];
s.dCAS    =   [0 kQ];
s.xCAS    =   [0;0];

[s.aCAS, s.bCAS] = C2DZOH( s.aCAS, s.bCAS, d.dT );
s.control        = d.control; % Nominal settings
s.pilotPitchRateInput = 0;
```

AircraftControlCAS.m

The update portion is shown below.

Listing 8.13: Updating the controller *AircraftControlCAS.m*

```
function [y, s] = Update( s, d )

% Pilot input
%-------------
if( d.pilotPitchRateInput.enter )
  s.pilotPitchRateInput = d.pilotPitchRateInput.value;
  disp(sprintf('New␣pitch␣rate␣input␣%12.4f', s.pilotPitchRateInput))
end

% Input
%------
input = [d.sensor.alpha; d.sensor.q];

% Control implementation
%-----------------------
yCAS   = -(s.cCAS*s.xCAS + s.dCAS*input);
s.xCAS = s.aCAS*s.xCAS + s.bCAS*[input(1);input(2) - s.pilotPitchRateInput];

% Output
%-------
s.control.elevator = yCAS;
y                  = s.control;
```

AircraftControlCAS.m

The results are shown in the following plots. A ± 1 deg/sec pitch rate doublet is commanded using the rst but- ton on the HUD. This corresponds to 0.017 rad/s, which is what we see in the plots. You may need to push the button a couple of times. The call to `disp` in the above listing prints into the command window to let you know that the command went through.

The HUD is shown in Figure 8.3 on the next page. The value of the desired pitch rate in deg/s (in this case "1") is entered into the text field next to "Button 1" before the button is pushed. In this example, we enter a $+1$, then a -1, then 0.

The pitch rate response in shown in Figure 8.4 on the following page, in the figure on the left. An initial negative pitch rate occurs to stabilize the aircraft from its slightly off-trim initial condition. Next the doublet is entered and tracked well. The figure on the right shows the elevator response.

Figure 8.3: HUD Display for `F16CAS` Demo

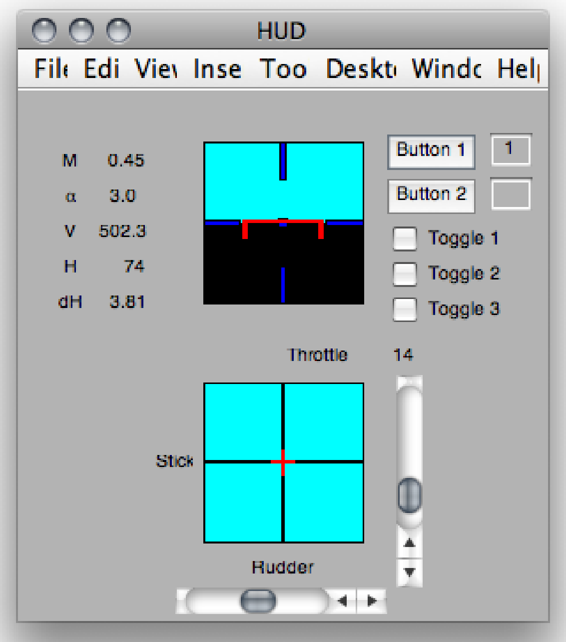
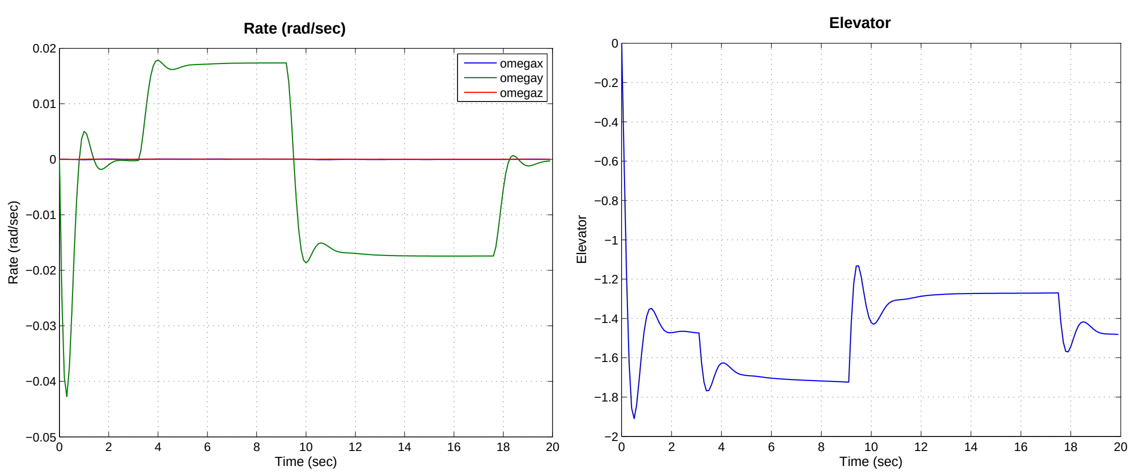


Figure 8.4: Pitch Rate Response for `F16CAS` Demo



CHAPTER 9

PERFORMANCE ANALYSIS

This chapter gives an overview of the tools for analyzing aircraft performance.

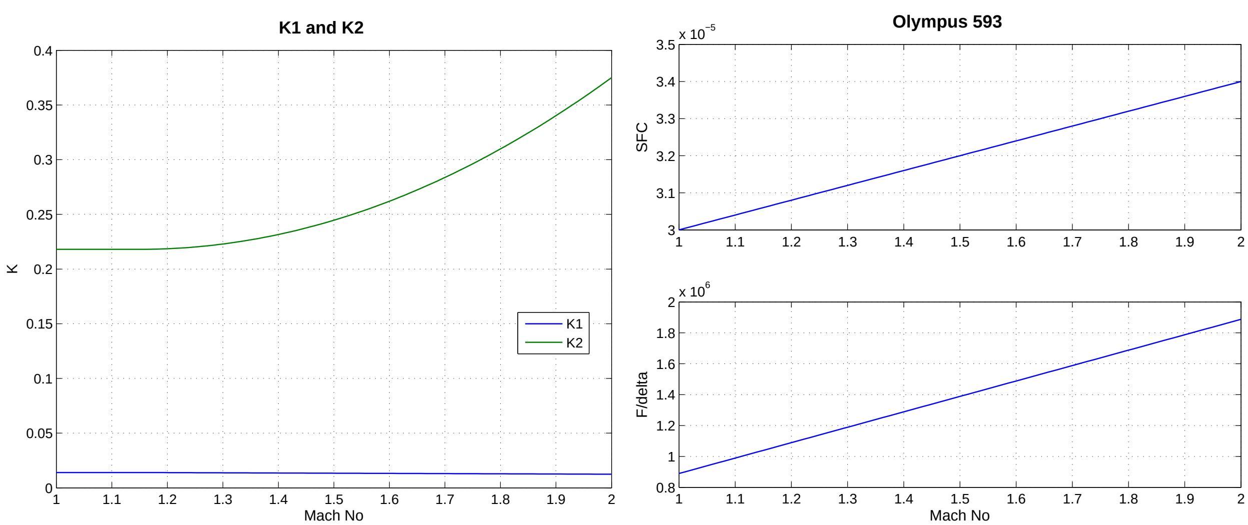
9.1 Concorde Properties

The `ConcordeProperties` function outputs a range of properties for the Concorde.

```
[d, def] = ConcordeProperties( machNo )
```

By just typing `ConcordeProperties` you can generate the following plots:

Figure 9.1: Concorde Properties vs. Mach No.



(a) Drag Polar Coefficients

(b) Specific Fuel Consumption (kg/N/s) and Thrust over Pressure Ratio (N)

The function also outputs the following data:

```
massDry                    Dry mass        kg or lbm
massFuel                   Fuel mass       kg or lbm
massDesign                 Design point for calculations   kg or lbm
```

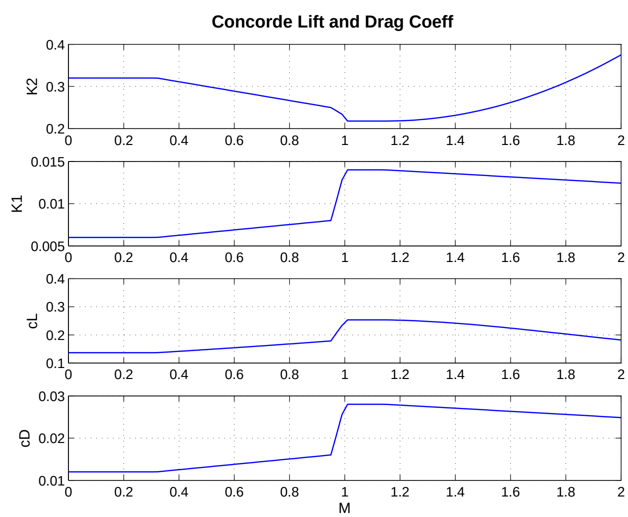
```
sFC                         Specific fuel consumption       kg/N/sec or lbm/lbf/sec
cL                          Lift coefficient
cD                          Drag coefficient
k1                          Drag polar coefficient 1
k2                          Drag polar coefficient 2
wingArea                    Wing area       m^2 or ft^2
wingLoading                 Wing loading    N/m^2 or lbf/m^2
name                        Name
cLCoeff                     Lift coefficient
cLMax                       Maximum lift coefficient
fOverDelta                  Force over P/P0          N or lbf
```

The lift and drag properties of the Concorde can be obtained using the `ConcordeLD` function. It is invoked as follows:

```
[cL, cD, k1, k2] = ConcordeLD( machNo );
```

where the input is Mach number. The function is valid for a Mach range of 1-2. Typing `ConcordeLD` produces the following plot:

Figure 9.2: Concorde Lift and Drag Properties vs. Mach No.



The values `k1` and `k2` are the drag polars, which relate the lift and drag coefficients according to the following equation:

$$C_D = k_1 + k_2 C_L^2$$

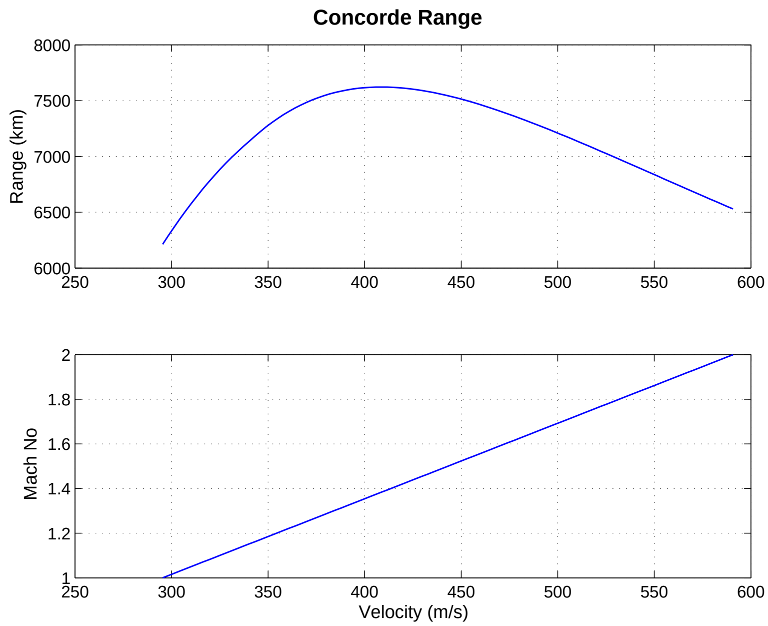
9.2 Breguet Range Equation

`BreguetRangeEquation` generates the Breguet range. The usage is:

```
>> range = BreguetRangeEquation( d, velocity, altitude )
```

where `d` is the data structure generated from `ConcordeProperties`. To get the demo, just type `BreguetRangeEquation` and the following figure is generated.

Figure 9.3: Breguet Range



9.3 Rate of Climb

The rate of climb and acceleration can be computed using:

```
>> [rateOfClimb, accel] = RateOfClimb( d, velocity, altitude )
```

where `d` is the data structure generated from `ConcordeProperties`. Type the function name with no inputs and no outputs to see a plot based on default data.

9.4 Takeoff

The `Takeoff` function computes the required roll distance and takeoff velocity, given a data structure of the type generated by `ConcordeProperties`, and the takeoff altitude. The usage is:

```
[sTotal, vLiftoff, def] = Takeoff( d, altitude );
```

Calling the function name by itself produces the following example:

```
>> Takeoff;
Ground roll      =       1753.0 m
Liftoff velocity =         78.8 m/s

       Field     Description    Units
       cLMax     Maximum Lift Coefficient
    wingArea     Wing area       m^2 or ft^2
 massTakeoff     Mass at takeoff         kg or lbm
         cDG     Drag coefficient on the ground
         cLG     Lift coefficient on the ground
         cDR     Drag coefficient in rotation
         cLR     Lift coefficient in rotation
    k2Engine     Engine thrust is f = fStatic*(1 + k2Engine*v + k3Engine*v^3
```

```
   k3Engine     See k2Engine
        muR     Drag decrease due to lift on the ground
    fStatic     See k2Engine
  tRotation     Rotation time   sec
```

9.5 Stall Velocity

Use `VStall` to compute the stall velocity.

```
>> vStall = VStall( d, altitude )
```

The data structure `d` must contain the maximum lift coefficient `cLMax`, the mass `massDesign` in kg, and the wing area `wingArea` in square meters. The built-in demo of the function produces a plot of stall velocity versus altitude.

CHAPTER 10

GAS TURBINES

This chapter describes the toolbox functions for the basic design and analysis of gas turbine engines.

10.1 Using the Jet Engine Functions

The jet engine functions let you design gas turbines and analyze their performance. There are three main functions, summarized below.

`JetEngineDefinitions.m`
Denes the data structures used in the other functions. Lists each eld of the input data structures.

`JetEngineAnalysis.m`
This function does cycle analysis of jet engines.

`JetEnginePerformance.m`
This function does performance analysis of an existing design including performance at partial throttle settings.

The functions cover a range of engines:

- Ramjet
- Single Spool Turbojet
- Dual Spool Turbojet
- Dual Exhaust Turbofan
- Mixed Exhaust Turbofan
- Turboprop

Any of the turbojet engines can have afterburners. The calling format for the analysis and performance functions are

```
>> [g, p, d, def] = FUNCTION( p, d );
```

where `p` is a data structure with parameters that you plan to vary during the analysis such as compressor pressure ratio and burner temperature. `d` is a data structure with parameters that are xed such as polytropic efciencies.

10.2 Using JetEngineDefinitions

`JetEngineDefinitions` gives you denitions of all of the elds in the data structures used by `JetEngineAnalysis` and `JetEnginePerformance`. If you type `JetEngineDefinitions` you will get a list of all engines and the inputs for both the analysis and performance functions. To get just the information for a particular engine combination type, for example,

```
>> JetEngineDefinitions('analysis','ramjet')

Function: analysis       Engine: ramjet

-------------
P parameters
-------------
altitude         Altitude        m       ft
machNo           Mach number
tT4              Combustor temperature   K       R

-------------
D parameters
-------------
analysis         'ideal' 'real'
cPC              Air specific heat       J/kg-K  Btu/lbm-R
cPT              Air/Fuel specific heat  J/kg-K  Btu/lbm-R
eD               Diffuser polytropic efficiency
engine           Engine name
etaB             Burner efficiency
gammaT           Burner ratio of specific heats
hPR              Fuel heating value      J/kg    Btu/lbm
m2               Mach number at the diffuser exit
p0OverP9         Inlet/outlet pressure ratio
piB              Burner pressure ratio
piDMax           Diffuser maximum pressure ratio
piN              Nozzle pressure ratio
units            'eng' or 'mks'
```

10.3 Using JetEngineAnalysis

Typing just the name `JetEngineAnalysis` will get you a demo. If you type:

```
JetEngineAnalysis('ramjet')
```

you will get a ramjet demo. Typing:

```
JetEngineAnalysis(p,d)
```

will plot the results. Typing:

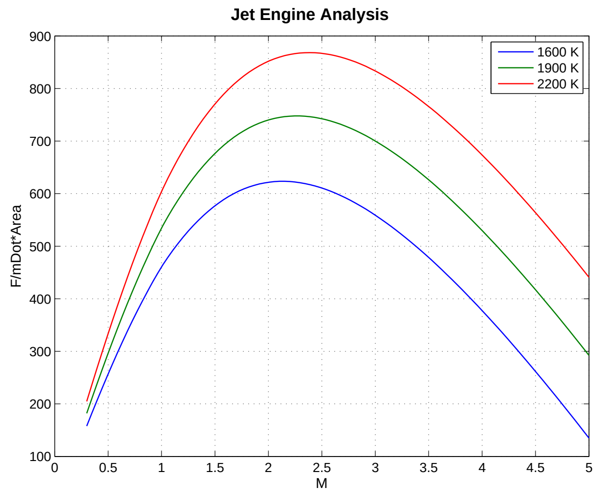
```
[g, d, p, def] = JetEngineAnalysis( p, d );
```

will put the results in `g` and echo `p` and `d` in the output. `def` gives you the denitions of `p` and d.

The following example shows how to analyze a ramjet.

Example 10.1 Jet Engine Analysis Demo

```
%---------------------------------------
%   Demo JetEngineAnalysis
%---------------------------------------
% Plot specific thrust as a function of
% mach number and combustion temperature
%---------------------------------------

p.tT4            = [1600 1900 2200];
p.altitude       = 12000;
p.machNo         = linspace(0.3,5);
d.cPC            = 1004;
d.cPT            = 1004;
d.hPR            = 42800000;
d.gammaT         = 1.4;
d.units          = 'mks';
d.eD             = 1.0;
d.etaB           = 1.0;
d.piB            = 1.0;
d.piDMax         = 1.0;
d.piN            = 1.0;
d.p0OverP9       = 1.0;
d.analysis       = 'real';
d.engine         = 'ramjet';
d.m2             = 0.4;

for k = 1:length(p.machNo)
  g = JetEngineAnalysis(p,d);
end

Plot2D(p.machNo,g.fOverMDotA,'M','F/mDot*Area','Jet␣Engine␣Analysis')
legend('1600␣K','1900␣K','2200␣K')
```



10.4 Using JetEnginePerformance

Typing just the name `JetEnginePerformance` will get you a demo. If you type:

```
JetEnginePerformance('ramjet')
you will get a ramjet demo. Typing:
\begin{codebit}
JetEnginePerformance(p,d)
```

will plot the results. Typing:

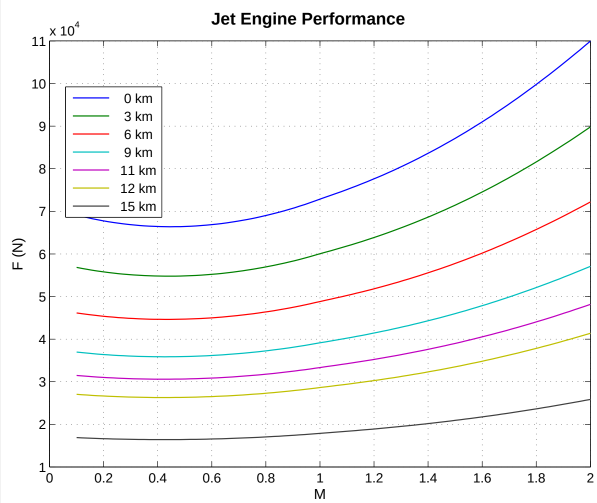
```
[g, d, p, def] = JetEnginePerformance( p, d );
```

will put the results in `g` and echo `p` and `d` in the output. `def` gives you the denitions of `p` and `d`.

The following listing shows a demo of a single spool turbojet.

Example 10.2 Jet Engine Performance Demo

```
%--------------------------------
%   Demo JetEnginePerformance
%--------------------------------
% Plot thrust as a function of
% mach number and altitude
%--------------------------------
p.altitude       = [0 3 6 9 11 12 15]*1e3;
p.machNo         = linspace(0.1,2);
p.p0OverP9       = 0.955;
p.tT4            = 1800;
p.controlOn      = 0;

d.units          = 'mks';
d.afterburner    = 0;
d.altitude       = 12000;
d.cPC            = 1004;
d.gammaT         = 1.3;
d.cPT            = 1239;
d.tT4            = 1800;
d.tT7            = 2400;
d.machNo         = 2;
d.piC            = 10;
d.tauC           = 2.0771;
d.tauT           = 0.8155;
d.piT            = 0.3746;
d.piDMax         = 0.95;
d.piD            = 0.8788;
d.piB            = 0.94;
d.piN            = 0.96;
d.etaB           = 0.98;
d.etaC           = 0.8641;
d.etaM           = 0.99;
d.p0OverP9       = 0.5;
d.hPR            = 42800000;
d.f              = 0.03567;
d.pT9OverP9      = 11.62;
d.m0Dot          = 50;
d.piCMax         = 12.3;
d.throttleRatio = 1.2;
d.engine         = 'single spool turbojet';

g = JetEnginePerformance(p,d);

Plot2D(p.machNo,g.force,'M','F (N)','Jet
    Engine Performance')
for k = 1:length(p.altitude)
  l{k} = sprintf('%4.0f km',p.altitude(k)
      /1000);
end
legend(l{:},0)
```



CHAPTER 11

AIRSHIPS

This chapter describes the toolbox functions for developing airship models and simulating their flight. Airships are lighter-than-air vehicles that utilize a buoyancy force to provide static lift. Traditionally, airships have fallen into two categories: pressurized and rigid. In a pressurized airship, a flexible, lightweight fabric forms the exterior envelope, and the shape of the hull is maintained by a slightly higher internal pressure. With rigid airships, a solid, interior frame maintains the shape. The tools provided in this software package deal only with pressurized airships.

The functionality of the airship code is divided into the following four topics:

- Modeling
- Control
- Analysis
- Simulation

All of the airship functionality is contained in the Airships folder. This folder is organized into four sub-folders according to the above topics. The remainder of this chapter describes the tools available under each category.

11.1 Modeling

An aerodynamic model of an airship may be built using the functions in the Modeling folder. The complete airship model consists of the hull, a single hanging gondola, and four symmetric fins.

The hull is modeled as a double-ellipsoid, with a front semi-major axis a_1, a rear semi-major axis a_2, and common radius b. The ratio of the rear ellipsoid to the front ellipsoid, k, is approximately 2 for the classic teardrop shape. One may choose the overall length L, diameter D, and ratio k, then use the following function to view the geometry:

```
>> DrawAirship( L, D, k );
```

The surface area and volume of the hull, as well as the ellipsoid axes, may be computed with:

```
>> [S, V, a1, a2, b] = AirshipGeometry( L, D, ratio );
```

THe total drag at a particular altitude h and velocity u may be computed using:

```
>> D = AirshipDrag( h, u, A, Cd );
```

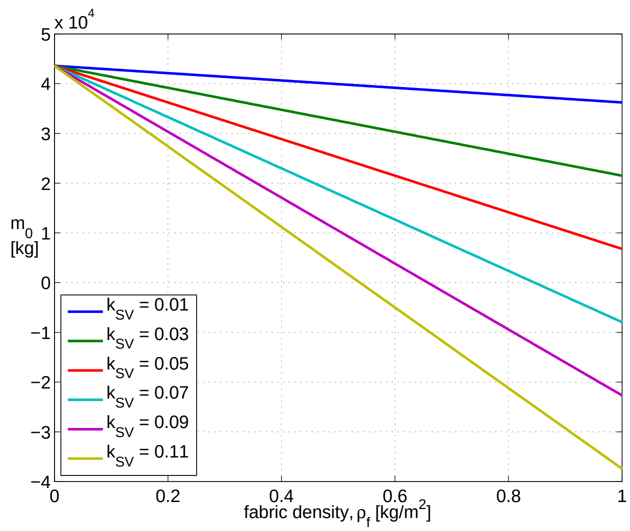
where A is the reference area and C_D is the drag coefficient.

The aerostatic properties of a pressure airship show that a constant buoyancy force is maintained up to a "pressure altitude//. The magnitude of the buoyancy force depends upon the volume of the hull and the density of the air at the pressure altitude. The airship should be designed so that the static lift of the buoyancy force can offset the weight of the vehicle. The function `StructuralMass.m` can be used to evaluate the feasibility of a given design with respect to its size and mass. The default inputs can be used to generate a plot by simply calling the function name:

```
>> StructuralMass
```

The following plot shows how the mass available for airship structure and systems varies with increasing fabric density, for a range of airship geometries. Each line represents a different value of k_{SV}, which is the ratio of hull surface area to volume.

Figure 11.1: Structural Mass Dependence on Geometry and Fabric Density



Clearly, as the fabric density increases, and as the surface-to-volume ratio increases (increasingly slender airship), the mass available for structure and systems decreases. The available mass is much higher for lower altitudes. This points to one of the key challenges in high-altitude airship design: the need for ultra-light materials.

Another type of trade-off analysis may be done with respect to the power. The maximum required power for nominal operation depends upon the drag, cruise velocity, and propeller efficiency. Additional power is likely required for the payload. A sufficient area of solar cells must be placed on the top of the airship hull in order to provide the required power. This area depends upon the required power, the solar cell efficiency, the global irradiance, and the daily fraction of sun-exposure. Given these parameters, the function `SolarCellCoverage.m` can be used to evaluate the required solar cell coverage for a particular hull geometry. To see a demo:

```
>> SolarCellCoverage
```

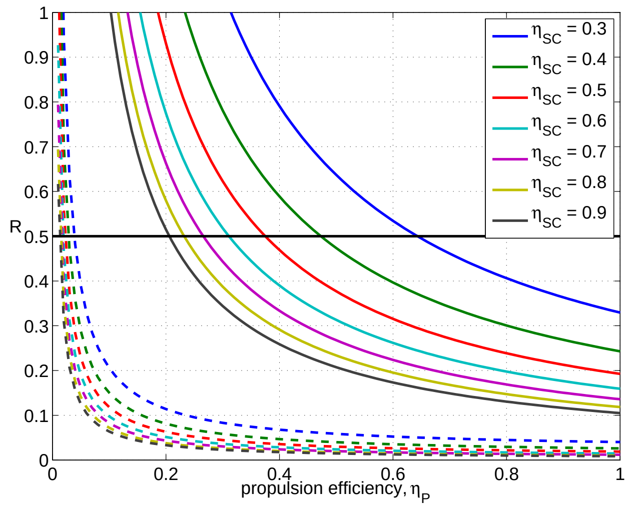
The following plot shows how the solar cell coverage ratio R varies with different levels of propeller and solar cell efficiencies. R is the ratio of required solar cell area to hull surface area. The required solar cell area is derived from the power requirement for extended operation of the turbines at a specified airspeed.

The top set of curves correspond to a maximum airspeed of 40 mph, and the lower set of curves are for 103 mph. These are the expected average and maximum windspeeds an airship would encounter over the U.S. at an altitude of 70k ft.

A graphical user interface may be used for conducting the high-level types of trade-offs discussed above. Just type:

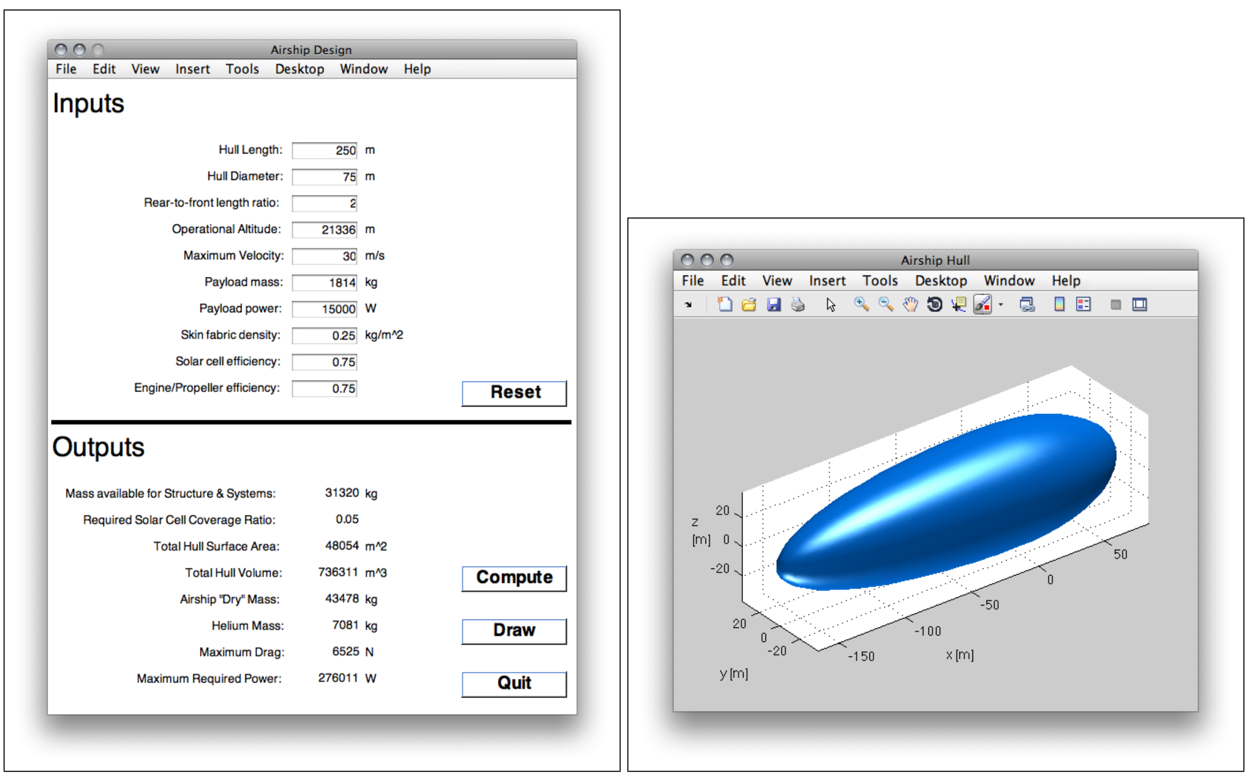
```
>> AirshipDesignGUI
```

Figure 11.2: Required Solar Cell Coverage Ratio vs. Efficiencies



to open the GUI. Change the input values on the top portion of the window, then press the "Compute" button to recompute all of the output values. Press the "Draw" button to bring up a 3D view of the airship hull.

Figure 11.3: Airship Design GUI



The general specifications for a particular airship model are included in the file `ASM1.m`, which is located in the Models folder. This may be used as a template and new variations of this model may be saved for your own design work. Type the following to obtain a data structure of the general model:

```
>> d = ASM1;
```

The parameters in `d` represent the high-level design parameters for the airship configuration. This data structure may be used to build an approximate aerodynamic model. To build an airship aero model, type:

```
>> m = BuildAirshipModel( name, xo );
```

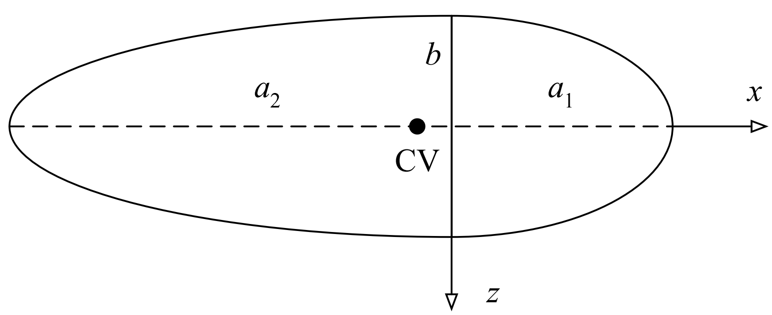
where `name` is the string name of the airship model file, and `xo` is the axial displacement of the body-frame origin, measured positive backwards from the nose. The coefficients and moment of inertia included within the aerodynamic model depend upon the location of the body-frame. If no inputs are provided, defaults are used (the default model name is 'ASM1').

11.1.1 Baseline Airship Design

This section describes a baseline airship design to provide an illustrative example for new users.

As previously noted, the airship hull is modeled as two half-ellipsoids. A diagram of the the x-z plane cross-section is shown in Figure 11.4. The total length is $L = a_1 + a_2$ and the maximum diameter is $D = 2b$. Note that this coordinate frame is aligned with the body frame, but the two frames are not coincident. The body frame is centered at the hull's CV, while this frame is located at the intersection of the two half-ellipsoids. Each half-ellipsoid is symmetric about

Figure 11.4: Double-Ellipsoid Model of Hull



the x-axis, and the rear ellipsoid is longer than the front, resulting in the classic "teardrop" shape.

Attached to the hull are four symmetric tail-fins and a hanging gondola, or empennage. The empennage supports the payload as well as two engines with counter-rotating propellers. The size and shape of the hull, and the size and location of the fins and gondola are defined in an *airship design script* in MATLAB. In addition to these geometric properties, you may also specify the payload mass, fabric density, and maximum altitude. The parameters that may be defined in the airship design script are summarized in Table 11.1.

Table 11.1: Airship Design Parameters

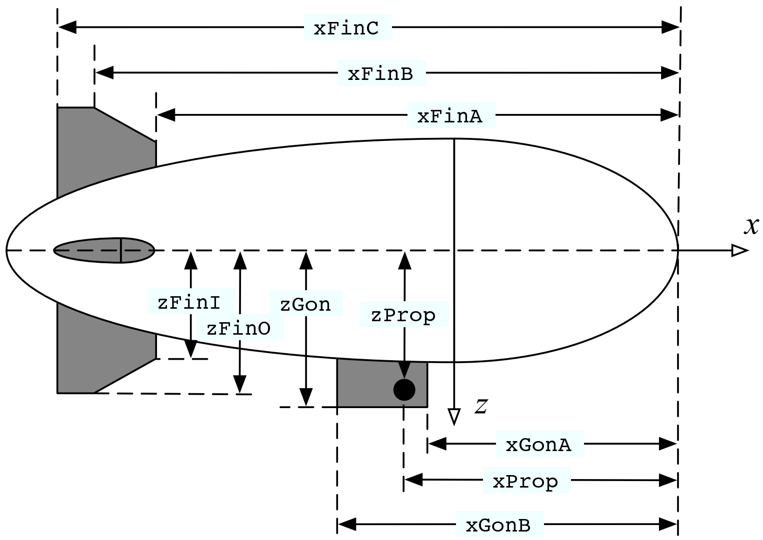
Parameter	Description	Units
`L`	Length of hull	m
`D`	Maximum diameter of hull	m
`ratio`	Ratio of rear ellipsoid length to front ellipsoid length, $a_2/a_1 > 1$	-
`alt`	Maximum altitude	m
`mP`	Payload mass	kg
`rhoF`	Fabric area density	kg/m^2
`xGonA`	x location of gondola L.E.	-
`xGonB`	x location of gondola T.E.	-
`zGon`	Minimum z location of gondola (g.t. 1)	-
`xFinA`	x location of fin L.E.	-
`xFinB`	x location of fin taper	-
`xFinC`	x location of fin T.E.	-

Table 11.1: Airship Design Parameters, contd.

Parameter	Description	Units
zFinI	Inboard length of fin	-
zFinO	Outboard length of fin	-
xProp	x location of propeller	-
zProp	z location of propeller	-
xPld	x location of payload	-

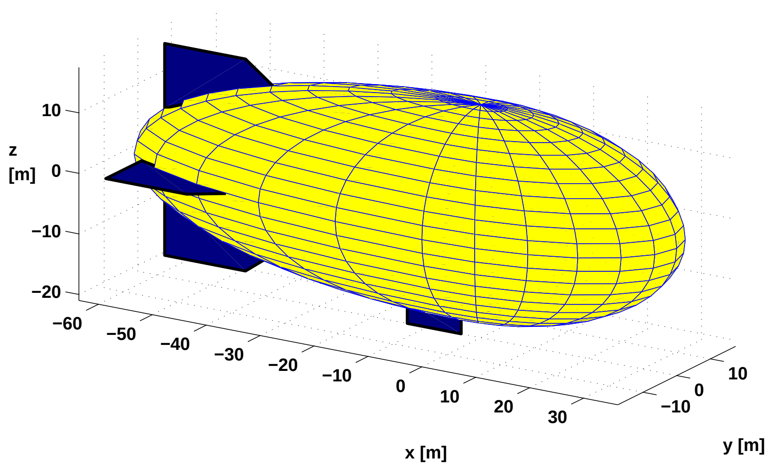
The x distances are measured back from the nose, and are non-dimensional in L. The z distances are measured down from the center axis, and are non-dimentional in b. Note that the z distances for the top/bottom fins apply to the y-axis dimensions of the right/left fins as well. The geometric parameters are illustrated in Figure 11.5 on the next page.

Figure 11.5: Airship Geometric Model



An example airship configuration is shown in Figure 11.6. This plot was generated automatically from the function `Airship3DLayout.m` by passing in the name of the airship design script. This function can be used to quickly visualize any airship design.

Figure 11.6: Example Airship Configuration



The design parameters for this configuration are summarized in Table 11.2. These values correspond to an airship geometry that was designed to meet critical force and energy balance constraints, and the dimensions are similar to those quoted by other institutions currently developing high-altitude airship prototypes.

Table 11.2: Example Design Parameters

Parameter	Value	Units
`L`	150	m
`D`	50	m
`ratio`	1.25	-
`alt`	21,336	m
`mP`	1363	kg
`rhoF`	0.08	kg/m^2

Table 11.2: Airship Design Parameters, contd.

Parameter	Value	Units
xGonA	0.35	-
xGonB	0.45	-
zGon	1.20	-
xFinA	0.75	-
xFinB	0.80	-
xFinC	0.95	-
zFinI	0.85	-
zFinO	1.00	-
xProp	0.35	-
zProp	1.20	-
xPld	0.385	-

11.2 Control

In order to develop a feedback control design for airships, it is instructive to work with a linearized model. The function `AirshipLinMod.m` may be used to quickly generate a linear model of a particular airship configuration at a chosen flight condition. The function is called as follows:

```
>> g = AirshipLinMod( m, h, theta, alpha, V );
```

where `m` is the aerodynamic model data structure (computed from `BuildAirshipModel`), `h` is the altitude in meters, `theta` is the pitch angle, `alpha` is the angle of attack, and `V` is the wind-relative velocity. The output `g` is a `statespace` object containing the continuous time A, B, C, D matrices.

The names of the inputs, outputs, and states of the linear model may always be obtained by typing:

```
>> get(g,'inputs')
>> get(g,'outputs')
>> get(g,'states')
```

and the A, B, C, D matrices may be obtained using:

```
>> [a,b,c,d] = getabcd( g );
```

One may wish to break the single linear model into its constituent longitudinal and lateral modes. This may be done with:

```
>> [gLat,gLon] = AirshipStatespace( g );
```

In order to obtain the linearized models, the trim condition must be computed. This is done with the function `AirshipTrim.m`. It is called with the same inputs as `AirshipLinMod`:

```
>> [T,mu,dElv] = AirshipTrim( d, h, theta, alpha, V );
```

With the linearized models in hand, you can use the control design techniques of your choice to develop a feedback control law for the airship at this operating condition.

The outputs are trim thrust `T`, propeller pitch angle `mu`, and elevator deflection `dElv`. This total deflection is to be applied to both the left and right elevators. The thrust is the total trim thrust. Therefore, with two engines (one on each side), each engine should produce half of this thrust.

For an example of controlled flight of an airship, you can view and run the function `AirshipControlDemo.m`. This function initializes the airship at 21.3 km altitude, with 24 m/s airspeed. A velocity increase of 5 m/s is commanded. A set of pre-designed controllers are loaded and used to form the feedback control loops.

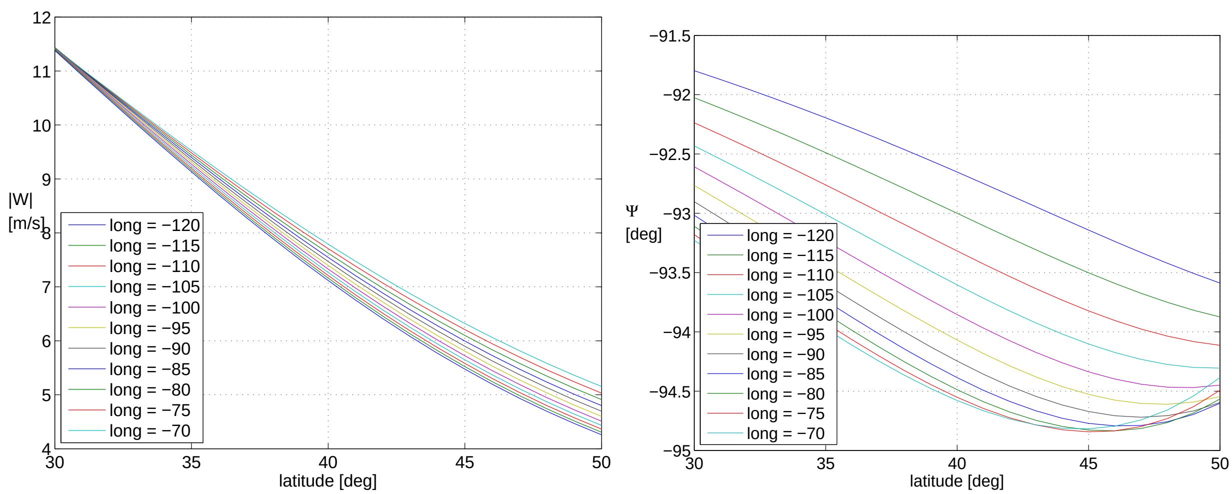
11.3 Analysis

Several tools are provided to enable immediate analysis of airship data.

- The latitude and longitude of several major U.S. cities may be computed by entering the name of the city
- The wind behavior at a particular day of the year and altitude may be computed for a range of latitudes and longitudes
- Linear models of a particular airship design may be computed for a range of flight conditions
- The aerodynamic forces and moments of a particular airship design may be computed over a range of flight conditions
- The control settings required for trim flight of a particular airship design may be computed over a range of flight conditions

The following plot was generated by the built-in demo included in `WindLatLon.m`. It shows the average magnitude and direction of the wind at 21.3 km altitude in the summer time over a range of latitudes and longitudes. The wind strength varies considerably with latitude, and very little with longitude. This data is generated using an empirical model that was developed by the Naval Research Laboratory.

Figure 11.7: Demo Results from `WindLatLon`



The control settings required for trim flight may be analyzed by calling two functions. First, compute the aerodynamic forces and moments for a variety of flight conditions by using the function `GenerateAirshipAeroMats.m`. It will compute matrices of forces and torques for a range of angles of attack and velocities at a particular altitude. Next, compute the required thrust, propeller pitch angle, and elevator deflection to achieve trim flight at these conditions:

```
>> data = GenerateAershipAeroMats;
>> data = AirshipTrimAnalysis( data );
```

11.4 Simulation

Airships are simulated within the Aircraft Control Toolbox in the same manner as regular aircraft. The 6 degree of freedom equations of motion for a rigid body are integrated using the standard 4th order Runge-Kutta method. The forces and moments due to gravity, aerodynamics, engines/propellers and disturbances are computed at each step. The effects of added mass and inertia are also accounted for, with the values of added mass and inertia provided by the aerodynamics function.

The functions used for the full non-linear airship simulation include:

AirshipAero – Compute the aerodynamic force and moment given the current state and flap deflections

AirshipSensor – Return the measured states (angular velocity, linear velocity, angle of attack, sideslip, altitude)

AirshipPropeller – Compute the applied thrust from throttle and propeller pitch commands

These names are provided to the simulation automatically by the `BuildAirshipModel.m` function. New models may be developed to substitute the originals for new airship designs. The appropriate model names must be included in the airship model data structure. Once a model has been built, the model names may be easily changed as follows:

```
>> m.aero.name     = 'NewAeroName';
>> m.sensor.name   = 'NewSensorName';
>> m.actuator.name = 'NewActuatorName';
>> m.engine.name   = 'NewEngineName';
```

An interactive demo is provided which allows you to “fly” the airship using a HUD (heads up display) interface. To initiate the demo:

```
>> FlyAirship
```

CHAPTER A

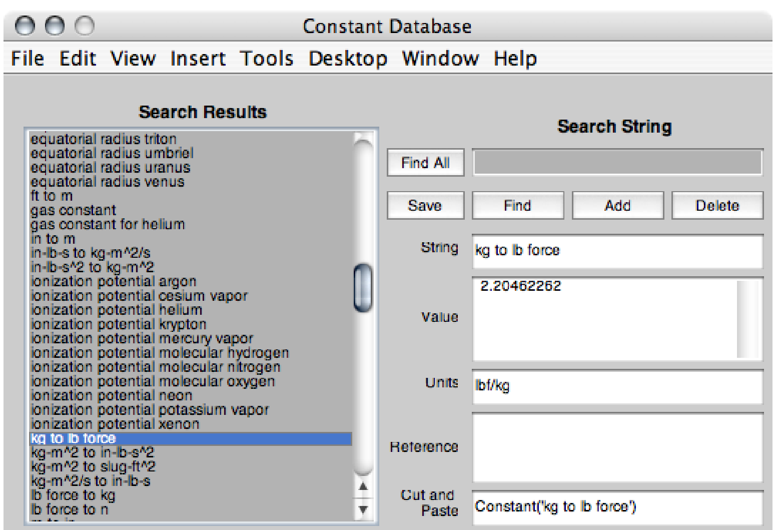
USING DATABASES

This chapter shows you how to use the database and constant functions in the toolboxes. These functions allow you to manage the various constants and parameters used in your projects and ensure that all of your engineers are using consistent numbers in their analyses.

A.1 The Constant Database

The constant database gives a substantial selection of useful constants. If you type `Constant` you will get the GUI in Figure A.1.

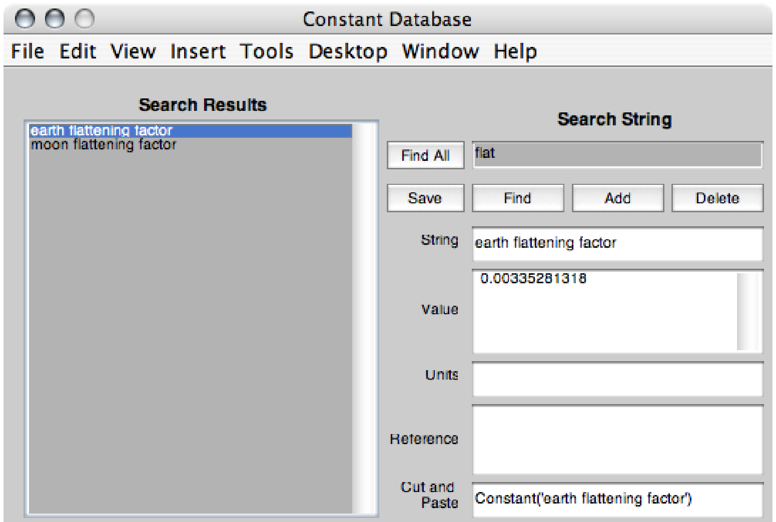
Figure A.1: Constant database



The list on the left is a list of all of the constants in the database. You can enter a search string and look for matches by hitting Find. If you then click one of the selections the GUI looks like it does in the following figure. This function always loads its constants from the `.mat` file `ACTConstants.mat`

The string field shows the parameter name. Directly below it is the value for the parameter. The value may be any MATLAB construct. Directly below that is a field for units, then a field for reference information and finally a field that gives a template for the function. You can cut and paste this into any function or script. Searches are insensitive to case and whitespace. Figure A.2 shows the database when searching for the string "flat". It finds the flattening factors for the Earth and Moon.

Figure A.2: Searching for flat



To add a new constant, type a name in the String field, a value in the value field and optionally, units and reference information. Hit Add. You will get a warning if you try to replace an existing constant. To modify the value of an existing constant, select the constant you wish to modify. Edit the value and hit the Add button. You can delete a constant by hitting the Delete button. You can access the database through the command line by passing the name of the desired constant to the function. For example:

```
>> Constant('equatorial_radius_earth')
ans =
                       6378.14
```

The database loads its constants from a database the first time it is launched. Once it is launched, it will not load a new database. However there is a fair amount of overhead involved in searching for a constant so we recommend that whenever possible you get the constant once from the database and store it in a local variable.

A.2 Merging Constant Databases

Periodically, PSS will release new constant databases. If you have customized your own database you can merge it with the PSS database using the `MergeConstantDB` function. Just type `MergeConstantDB( initialize, a, b )` where `a` and `b` are the `.mat` files to be merged. The standard PSS database for ACT is called `ACTConstants.mat`. This will bring up a GUI with two columns. If there are constants in each of the two databases being merged that have different values, you can use the GUI to choose the preferred value. Just click the button for the column you wish to include in `ACTConstants.mat`.

CHAPTER B

REFERENCES

B.1 About the References

References [B.1] through [B.4] are essential references for anyone designing aircraft control systems.

Ref. [B.1] covers most of the material in this toolbox and explains in detail how to use all of the control and simulation tools. It is an easily accessible text and is very well written. It covers all forms of control design techniques that are applicable to aircraft. It is the ideal companion volume for this toolbox.

Ref. [B.2] covers the modeling of aircraft in great detail. If you are interested in building your own simulation models, and creating your own properties databases, then this book is an excellent source of information.

Ref. [B.3] is a classic book with interesting approaches to SISO and MIMO control. It also has a great deal of information on aircraft modeling.

Ref. [B.4] covers the application of linear quadratic regulator techniques to both aircraft and spacecraft. It is very well written and clearly explains all of the fundamental principles of aerospace control design.

B.2 Reference Books

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