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BACT Simulation User Guide (Version 7.0)

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1. Introduction

This report documents the structure and operation of a simulation model of the Benchmark Active Control Technology (BACT) Wind-Tunnel Model shown in Figure 1. The BACT system was designed, built, and tested at NASA Langley Research Center as part of the Benchmark Models Program.[1,2,3] and was developed to perform wind-tunnel experiments to obtain benchmark quality data to validate computational-fluid-dynamics and computational-aeroelasticity codes, to verify the accuracy of current aeroservoelasticity design and analysis tools, and to provide an active controls testbed for evaluating new and innovative control algorithms for flutter suppression and gust load alleviation. The BACT system has been especially valuable as a control system testbed.

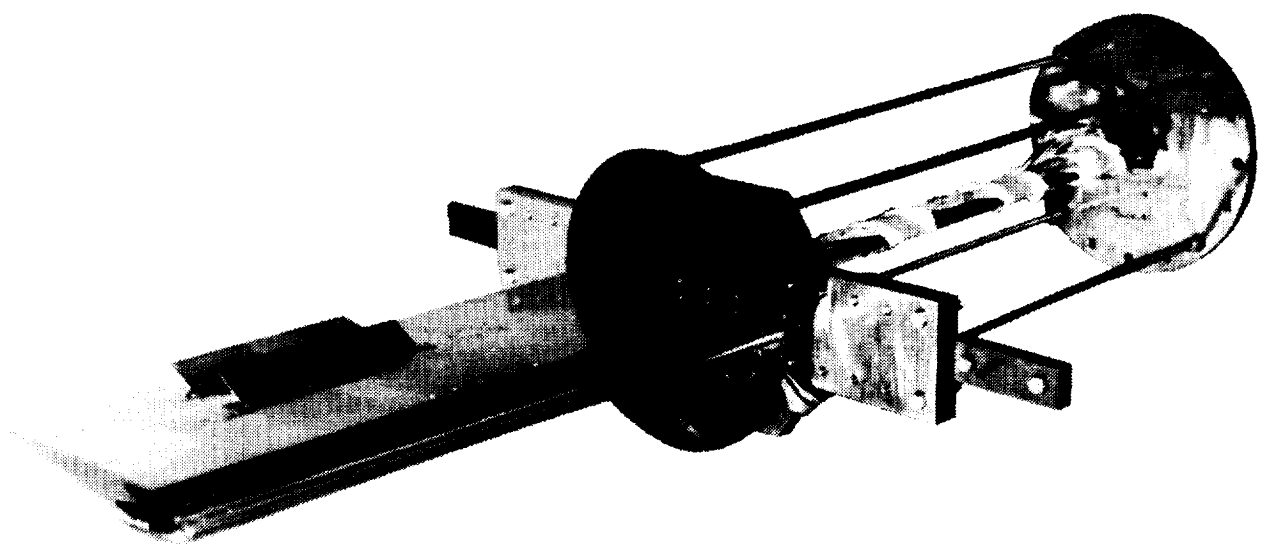

Figure 1 - Photograph of BACT Wind-Tunnel Model

The simulation model was developed to support the design and analysis of flutter suppression and gust load alleviation controllers. The simulation is written for MATLAB™ and SIMULINK™ and is structured to be very user friendly. The simulation model described herein has been used to assist the design and analysis of BACT controllers (primarily flutter suppression systems) using a variety of design methods including classical nyquist methods, H∞, μ-synthesis, generalized predictive control (GPC), and neural-networks.[4,5]

This report is organized to take the new user step-by-step through the various elements of the simulation model and the auxiliary modules that complement the simulation. While the simulation is quite simple and can be used with little background information this report provides additional details that will be of interest to the control system designer or more serious user.

It is assumed that the reader is familiar with MATLAB™ and SIMULINK™ and the structure of m-files and S-functions. If additional background is needed refer to References [6], [7], and [8]. All the m-files described herein were developed and tested using MATLAB™ Version 4.2c.1 and SIMULINK™ Version 1.3 and have not been tested with other versions of the software.

The BACT simulation package is freely distributable. However, please keep this document and the release notes with the other files. Do not distribute modified versions of the simulation without indicating (in the documentation and in the code itself) that changes have been made. In addition, please forward any bug fixes or significant improvements to the author.

2. Basis for Simulation

The simulation model and auxiliary tools are based on equations of motion for the BACT system, the control surface actuators, and a spectrum of wind-tunnel turbulence. The development and analysis of these elements are documented in references [9] and [10]. Reference [9] describes the development of the equations of motion for the BACT system from first principles. It also presents the actuators and turbulence models used in the simulation. Reference [10] describes how the actuator models were obtained from experimental data. Please refer to these documents for detailed information regarding the basic equations and numerical data.

3. File Structure

3.1 Simulation m-Files

All the files required to run the BACT simulation are contained in the BACT Sim4Xport folder shown in Figure 2. Table 1 describes the type and purpose of each file

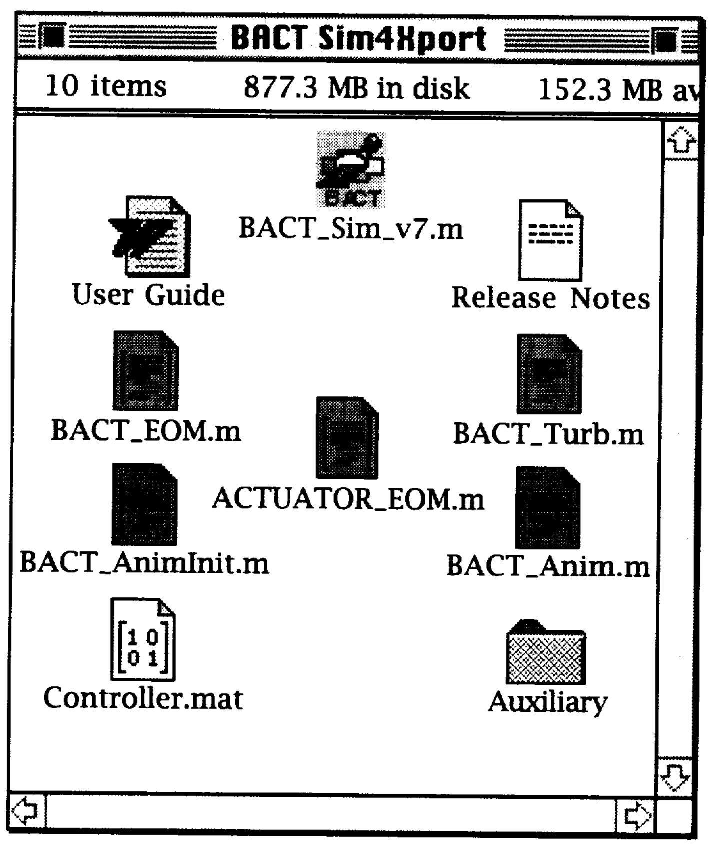

Figure 2 - BACT Sim4Xport Folder Window

Table 1 - BACT Simulation File Descriptions

Filename	Type	Description
BACT_Sim_v7.m	S-function	version 7 of the BACT simulation diagram
BACT_EOM.m	m-file	generates state space model of BACT system
ACTUATOR_EOM.m	m-file	generates state space model of BACT actuators
BACT_Turb.m	m-file	generates state space model of wind-tunnel turbulence
Controller.mat	MATLAB data	sample multivariable flutter suppression controller
BACT_AnimInit.m	m-file	initializes the BACT animation feature
BACT_Anim.m	m-file	enables animation of BACT system for enhanced visualization of system behavior
Release Notes	SimpleText	release notes of BACT simulation
Auxiliary	folder	contains additional BACT-related files
User Guide	Word 6.0	this document

The m-files are essentially self-documented. Following are the header sections of the key m-files which describe their usage and other vital information.

BACT_EOM.m :

```
% Usage [ap,bp,cp,dp]=BACT_EOM(q)
%
% BACT_EOM (V.6) generates a simplified state-space model
% for the dynamics of the BACT wind-tunnel model at a
% specified dynamic pressure value (psf).  It
% assumes that the aerodynamics can be represented by a
% 2-D quasi-steady approximation.  The numerical data is
% valid only for a Mach number of 0.77 in an R-12 fluid medium.
%
%  Additional information about the model is available in
%  AIAA Paper 96-3437 - "Modeling the Benchmark Active Control
%  Technology Wind-Tunnel Model for Application to Flutter Suppression."
%
%          INPUTS:      q       Dynamic Pressure (psf)
%
%          OUTPUTS:     ap      (4x4)  A-matrix
%                       bp      (4x8)  B-matrix[ te_accel   te_rate    te_defl
%                                                us_accel   us_rate    us_defl
%                                                gust_accel gust_velocity      ]
%                       cp      (4x4)  C-matrix[ li accel, ti accel, h, theta ]
%                       dp      (4x8)  D-matrix
```

Actuator_EOM.m :

```
% Usage [aa,ba,ca,da]=ACTUATOR_EOM(ka,wa,za)
%
% ACTUATOR_EOM generates a state-space model of
% a second order actuator given a gain, frequency
% and damping value.  The gain multiplies the
% square of the frequency to form the numerator of
% the transfer function.  The output includes the commanded
% deflection and the associated rate and acceleration.
% This form of the model is intended to provide input
% to the BACT equations of motion.
%
%  Additional information about the actuator model is available in
%  AIAA Paper 96-3362 - "Parameter Estimation and Analysis of
%  Actuators for the BACT Wind-Tunnel Model."
%
%  Input:        ka     gain
%                wa     freuquency  (rad/sec)
%                za     damping ratio
%
%  Output:       aa     A-matrix
%                ba     B-matrix        Input Vector :  [ actuator command ]
%                ca     C-matrix        Output Vector:  [ accel, rate, position ]
%                da     D-matrix
```

BACT_Turb.m :

```
% Usage: [ag,bg,cg,dg]=BACT_Turb(V)
%
%  TDT Turbulence Model - This function computes a state space
%  representation of a Dryden model of turbulence for the Transonic
%  Dynamics Tunnel based on spectral data presented in NASA TM 107734
%  "Characteristics of Vertical and Lateral Tunnel Turbulence Measured
%  in Air in the Langley Transonic Dynamics Tunnel."  Note that the data
%  corresponds to conditions at atmospheric pressure and in an air medium.
%
%  The parameters that appear in the Dryden Spectrum are dependent on
%  flow velocity and vary widely.
%
%   Input:        V              Reference speed for turbulence model
%                                  Valid Values = 100, 200, 300, and 400 fps
%                                  Preferred Value = 400 fps
%
%  Output:        ag,bg          State space matrices of turbulence model
%                 cg,dg          Output matrices - outputs are rate of change
%                                  of vertical velocity and vertical velocity,
%                                  wg-dot and wg, in units of ft/sec^2 and ft/sec
```

3.2 Auxilliary m-Files

Three additional m-files are included with the simulation to support analysis and control system design for the BACT system. They are contained in the Auxiliary folder which is shown in Figure 3. These files provide additional flexibility for the user if all that is needed are state space models of the BACT system or its elements.

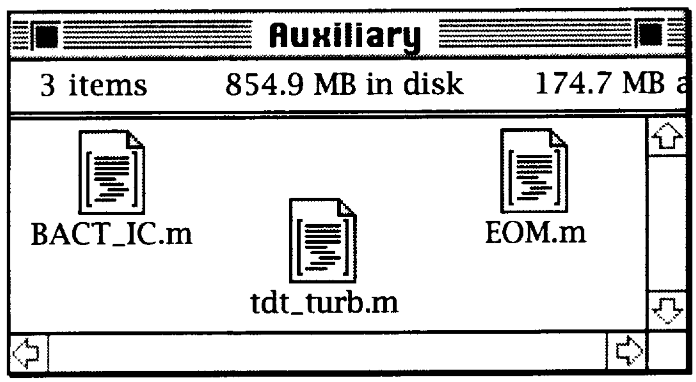

Figure 3 - Auxiliary Folder Window

These m-files are also essentially self-documented. Following are the header sections of each m-file describing its usage and other vital information.

BACT_IC.m :

```
% Usage: [z0,a0]=BACT_IC(q,TT,TE,US)
%
% BACT_IC computes the initial conditions of the BACT wind-tunnel
% model based on a simplified model of the system and given the
% dynamic pressure, q (psf), the turn-table angle, TT (deg), and the
% control surface biases, TE and US (deg). The initial conditions are
% the vertical displacement, z0 (in) and the pitch displacement, a0 (deg),
% relative to the static equilibrium with q=0.
%
%  INPUTS:     q          Dynamic Pressure (psf)
%              TT         Turntable Angle (deg, positive nose up)
%              TE         TE Control Surface Bias (deg, positive down)
%              US         US Control Surface Bias (deg, negative up)
%
% OUTPUTS:     z0,a0      Quasi-Static Vertical Deflection (in, positive up)
%                           and Pitch Deflection (deg, positive nose up)
```

tdt_turb.m : (virtually identical to BACT_Turb.m except that a menu option is included)

```
% Usage: [ag,bg,cg,dg]=tdt_turb(V)
%
% TDT Turbulence Model - This function computes a state space
% representation of a Dryden model of turbulence for the Transonic
% Dynamics Tunnel based on spectral data presented in NASA TM 107734 -
% "Characteristics of Vertical and Lateral Tunnel Turbulence Measured
```

```
% in Air in the Langley Transonic Dynamics Tunnel." Note that the data
% corresponds to conditions at atmospheric pressure and in an air medium.
%
% The parameters the appear in the Dryden Spectrum are dependent on
% flow velocity and vary widely. The user is given the opportunity to
% select the reference velocity from a menu of four choices or supply the value as
% an input to the function.
%
% Input:        V            Reference speed for turbulence model (optional)
%                              Valid Values = 100, 200, 300, and 400
%                              (Preferred Value = 400)
%
% Output:       ag,bg        State space matrices of turbulence model
%               cg,dg        Output matrices - outputs are rate of change
%                              of vertical velocity and vertical velocity,
%                              wg-dot and wg, in units of ft/sec^2 and ft/sec
```

EOM.m :

```
% Usage:  [a,b,c,d,q_value]=EOM(q,a_flag,Vturb)
%
% Version 12a -- 12/30/96
%
% This function forms a linear model of the BACT with actuators models
% for both trailing edge and upper spoiler controls and a Dryden model
% of tunnel turbulence. The inputs are control surface deflection commands
% (in deg) and a random turbulence input. The outputs are accelerations
% at points near the leading and trailing edges of the wing-section (in g's).
%
% All inputs are optional. The user is prompted for input if not included in
% function call. If no outputs are provided this header will be printed.
%
% Inputs:       q            dynamic pressure (psf)
%               a_flag       sets whether actuators and turbulence
%                             models are augmented to the BACT EOM's
%                                   'y' - include actuators and turbulence
%                                   'n' - no actuators or turbulence models
(default)
%                                    (note: if a_flag and Vturb are omitted in the
%                                      function call the default is a_flag='n')
%               Vturb        reference velocity for turbulence (ft/sec)
%                             allowable values: 100, 200, 300, 400 (default)
%
% Outputs:a,b,c,d      state space quadruple (see documentation for
%                             state vector, input and output vector definitions)
%               q_valueoptional string variable identifying the dynamic
%                              pressure associated with the model
```

4. Simulation Diagram

The interface to the BACT simulation is through the SIMULINK™ simulation diagrams. These diagrams appear as MATLAB™ windows when BACT_Sim_v7.m is executed. There are many variables in the simulation that can be controlled by the user. The primary ones are the dynamic pressure of the airflow and the control law used for feedback. The system elements have been designed (using masked blocks) so that changing simulation parameters is quite easy. Each of the variables that can be altered by the user are described below.

4.1 Main Diagram

The simulation diagrams are nested to make it relatively easy to operate the simulation. The main diagram is shown in Figure 4. There are several types of blocks that appear in this diagram. The key ones are the BACT EOM block and the subsystem blocks for the actuators, turbulence, and controller. There are also several other blocks that perform various functions including variable gains, multiplexing and de-multiplexing blocks, scopes, and summers.

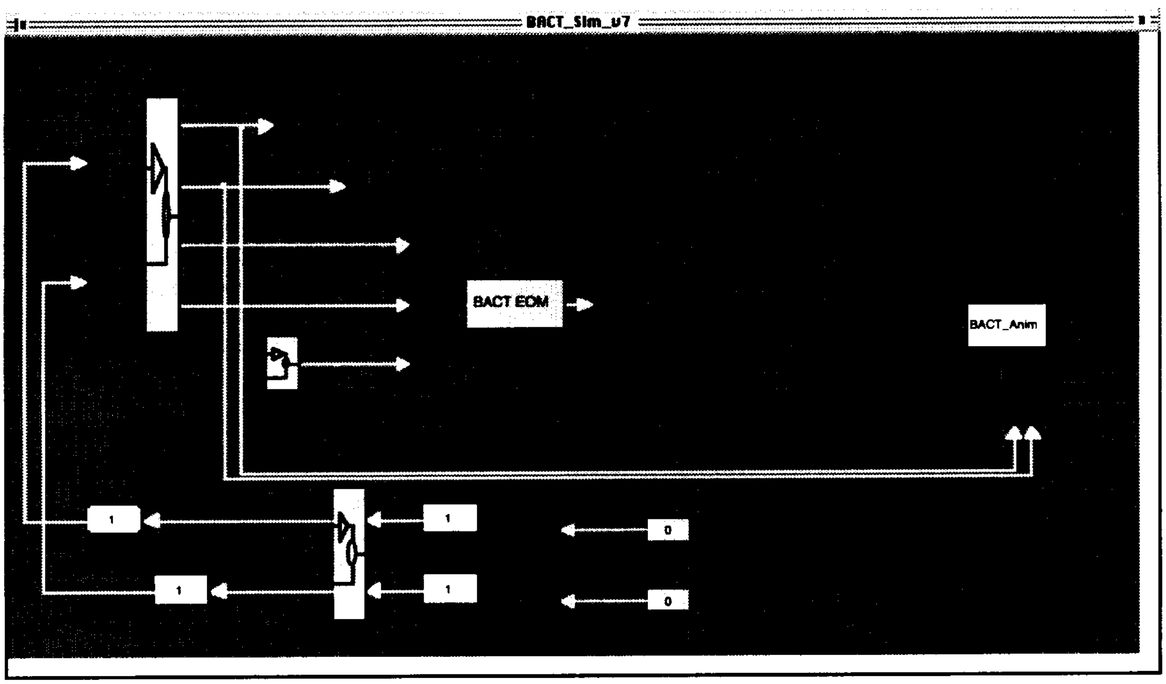

Figure 4 - BACT Simulation Diagram

4.1.1 BACT EOM Block

The BACT EOM block executes the m-file BACT_EOM.m and is used to generate a state space model of the BACT for a specific dynamic pressure. It is also used to introduce nonzero initial conditions on the state-space model. The dynamic pressure and initial state vector are input using a dialog box as shown in Figure 5. The dynamic pressure is entered in units of pounds per square foot. The initial conditions correspond to those of the states for the BACT EOM's -- vertical velocity (ft/sec, positive down), pitch rate (rad/sec, positive nose up), vertical displacement (ft, positive down), and pitch angle (rad, positive nose up). Therefore, the example in Figure 5 indicates that the dynamic pressure is 175 psf, and the initial condition is a downward vertical displacement of 0.01 ft and a nose up pitch angle of 0.01 radian.

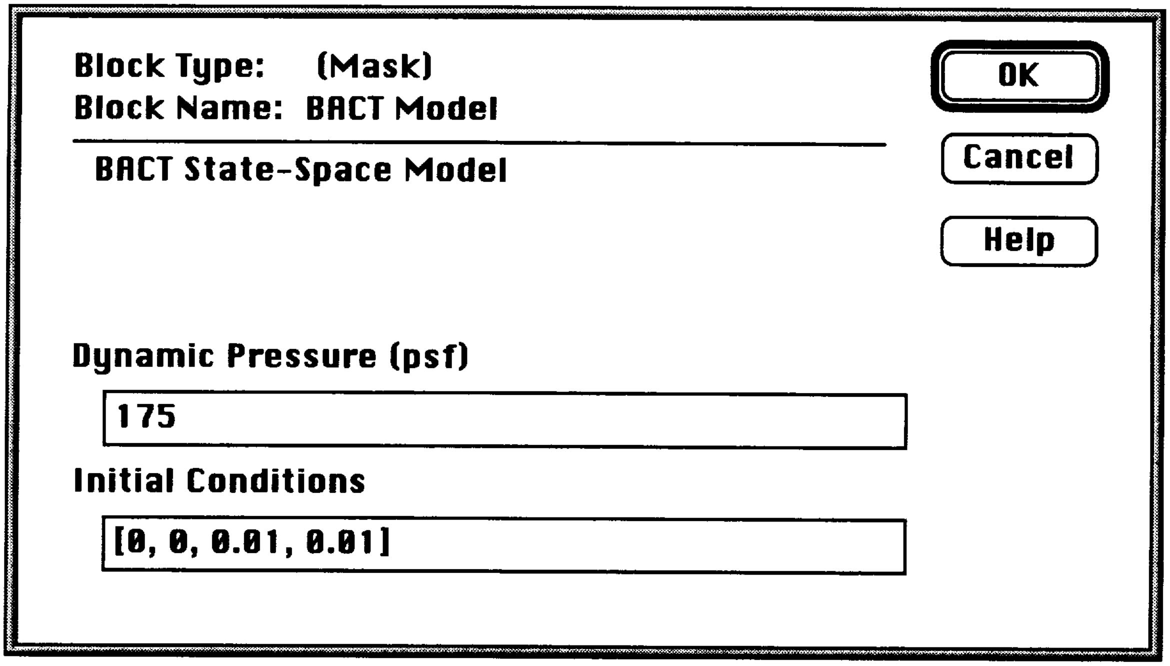

Figure 5 - BACT EOM Block Dialog Box

4.1.2 Gain Blocks

There are several variable gain blocks throughout the main simulation diagram. These blocks can be used to assess the robustness of candidate controller designs to sensor biases and gain variations in the individual controller input and output channels. Each gain is set using a slider similar to that shown in Figure 6. The user can change the minimum and maximum gain limits using the text boxes and the actual gain value using either the middle text box or the slider. This can be done while the simulation is running.

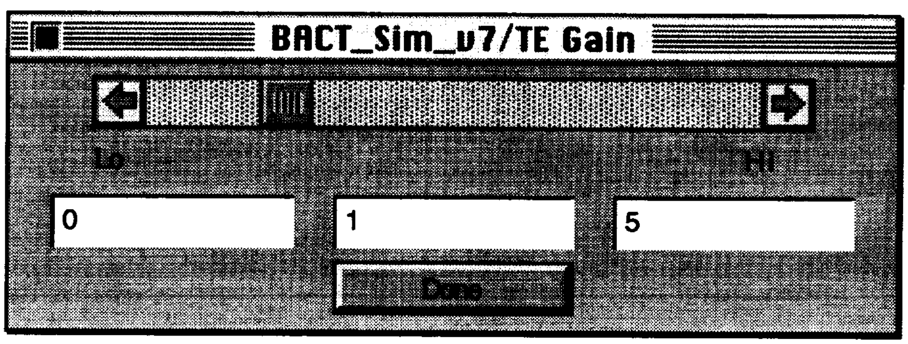

Figure 6 - Example Variable Gain Block Dialog Box

4.1.3 Mux, Demux, and Summer Blocks

Mux and Demux blocks are used to combine scalar signals into vector signals and vice versa to simplify the diagram and to provide appropriate input dimensions for other blocks.

Summer blocks are used to combine signals with the desired signs. Note that the TE Summer and US Summer are used to generate negative feedback. This is important to keep in mind when designing controllers that will be implemented in the controller subsystem.

4.1.4 Scope Blocks

Scopes are used to graphically display the changes in key system parameters over time. Figure 7 depicts the scope for the vertical displacement response. The user can control the vertical and horizontal scale using the text boxes.

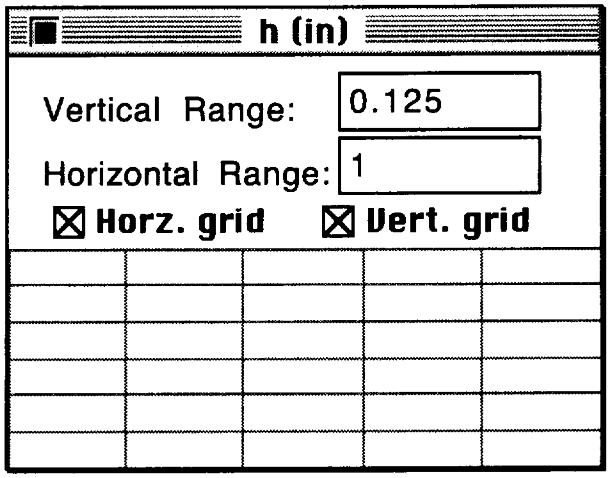

Figure 7 - Example Scope Block

4.1.5 Animation Block

The animation block is used to generate a simple "stick-figure" animation of the BACT wing-section to assist the user to visualize the dynamic behavior of the system. Figure 8 shows a sample frame of the animation. Note that the motions shown in the animation are not to scale (they are greatly magnified) and

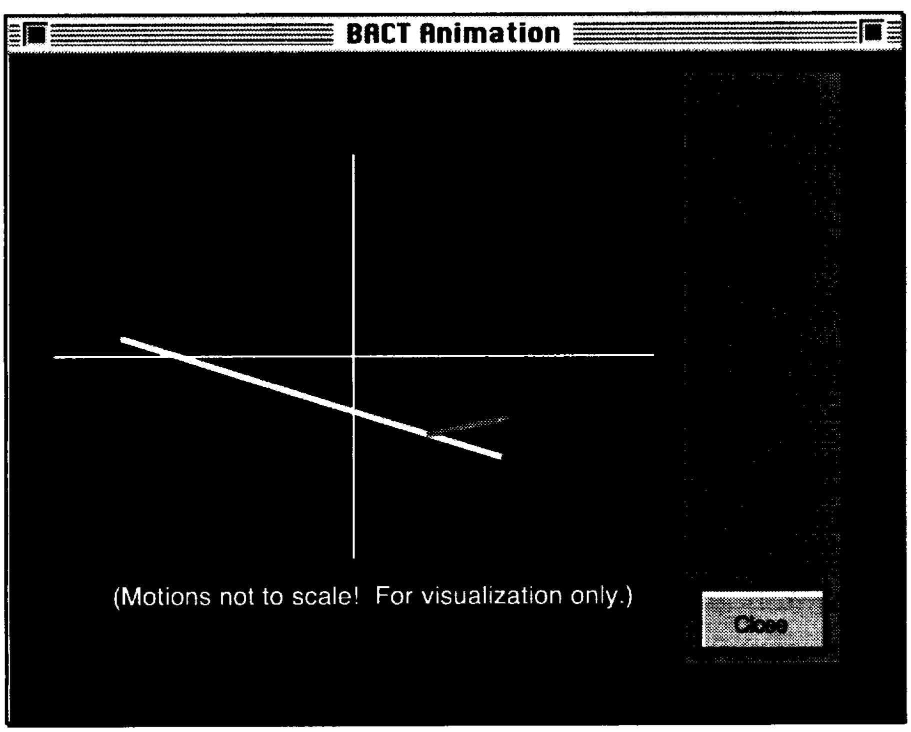

Figure 8 - Sample Frame from BACT Animation

are only intended for visualization purposes, and that the air flow direction is from left to right. The m-files BACT_Anim.m and BACT_AnimInit.m generate the animation. These were adapted from a SIMULINK™ demo animation that shipped with the Version 1.3.

This block causes the simulation to run much slower than it otherwise would and severely limits the control the user has over the simulation. In order to get complete control of the simulation and/or speed it up simply click on the close box in the animation frame. The animation window will close and control of the mouse and keyboard will return.

4.1.6 Subsystem Blocks

The last type of blocks that appears in the main simulation diagram are subsystem blocks. These blocks are used primarily to make the diagrams more readable and easy to understand. There are four of these subsystem blocks. The diagrams for the signal combinations, actuator, turbulence, and controller subsystems are discussed below.

4.2 Signal Combinations Subsystem Diagram

The Signal Combinations subsystem consists of Mux and Demux blocks to combine the various signals for input to the BACT EOM block. Figure 9 depicts the subsystem diagram. The definition of the input vector for the BACT state space model are evident from the labels on the various signals. Needless to say, this order is critical and must not be altered.

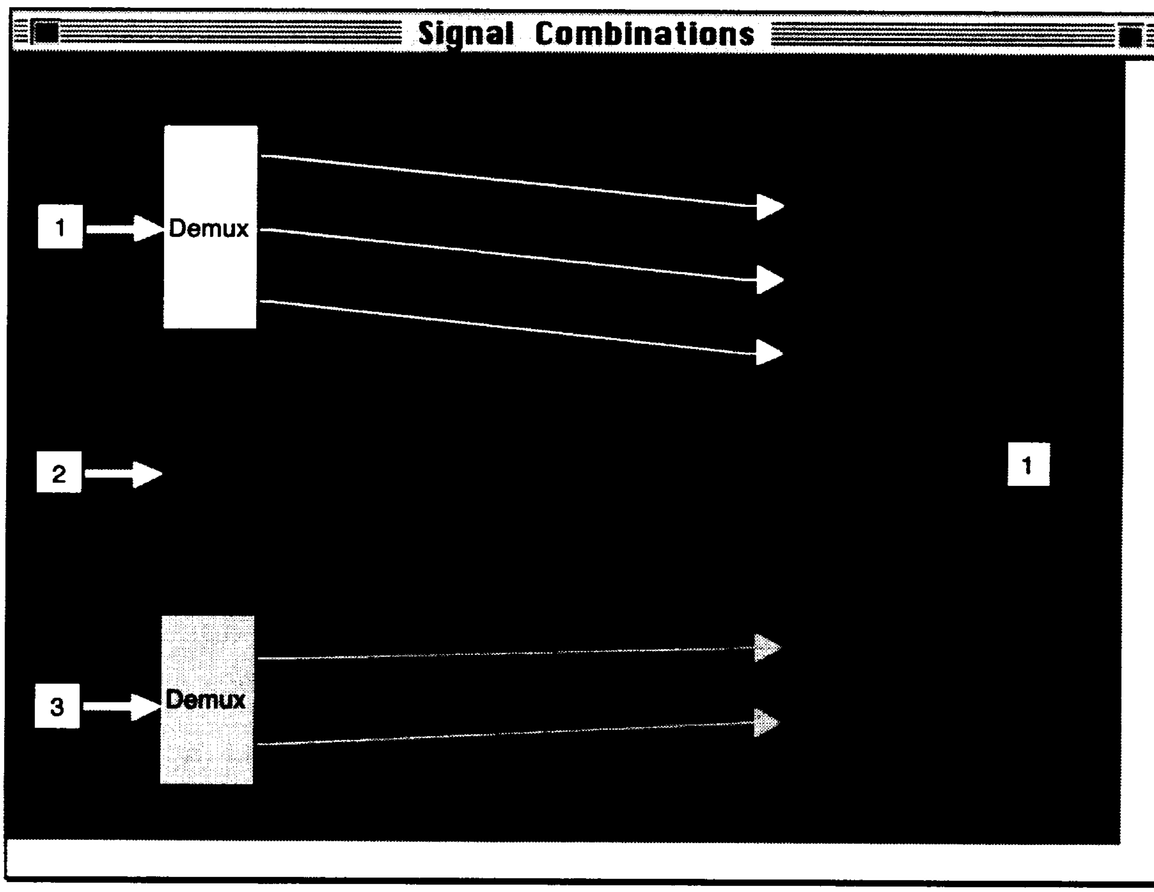

Figure 9 - Signal Combinations Subsystem Diagram

4.3 Actuator Subsystem Diagram

The actuator subsystem consists of two types of blocks -- the Actuator EOM blocks and the Actuator Nonlinearities Subsystem Blocks. Figure 10 depicts the actuator subsystem diagram

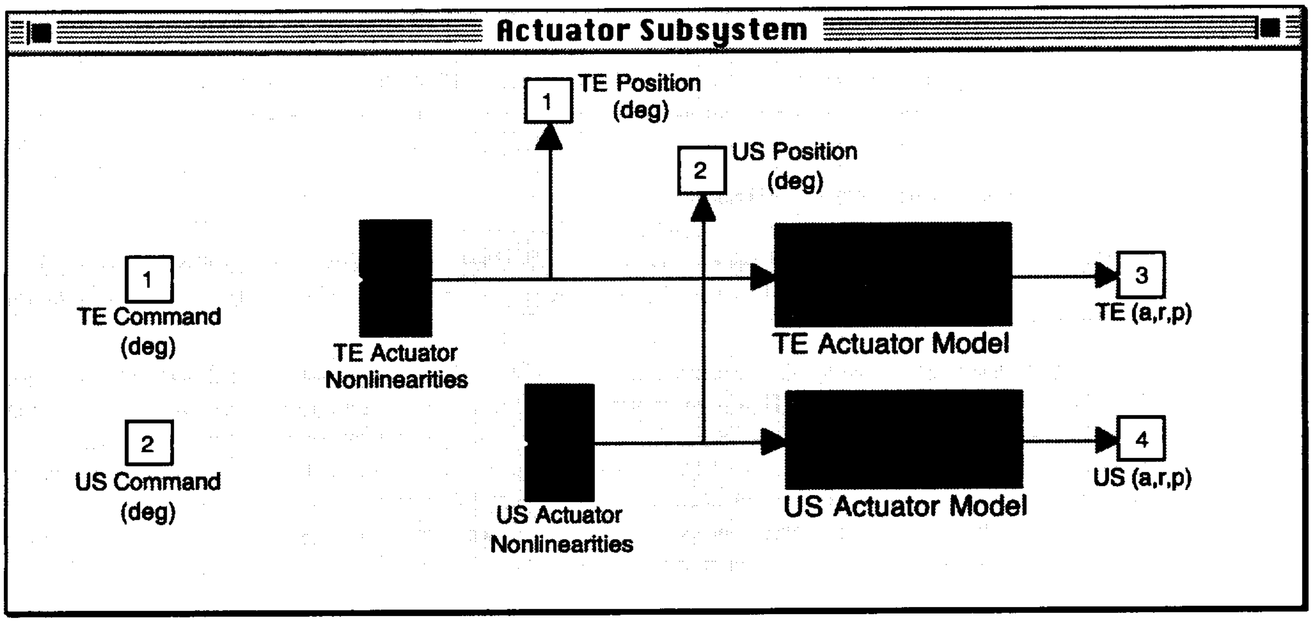

Figure 10 - Actuator Subsystem Simulation Diagram

4.3.1 Actuator EOM Blocks

The Actuator EOM blocks are masked blocks that execute the m-file ACTUATOR_EOM.m and allows the user to generate a second order state space model of the BACT actuators by entering three parameters – the actuator gain, and the frequency and damping of the second order dynamics. Figure 11 shows an example of the actuator dialog box. The values that appear by default were obtained from Reference [7] and correspond to the actual BACT actuators. Table 2 presents the default values for the trailing edge and upper spoiler actuators.

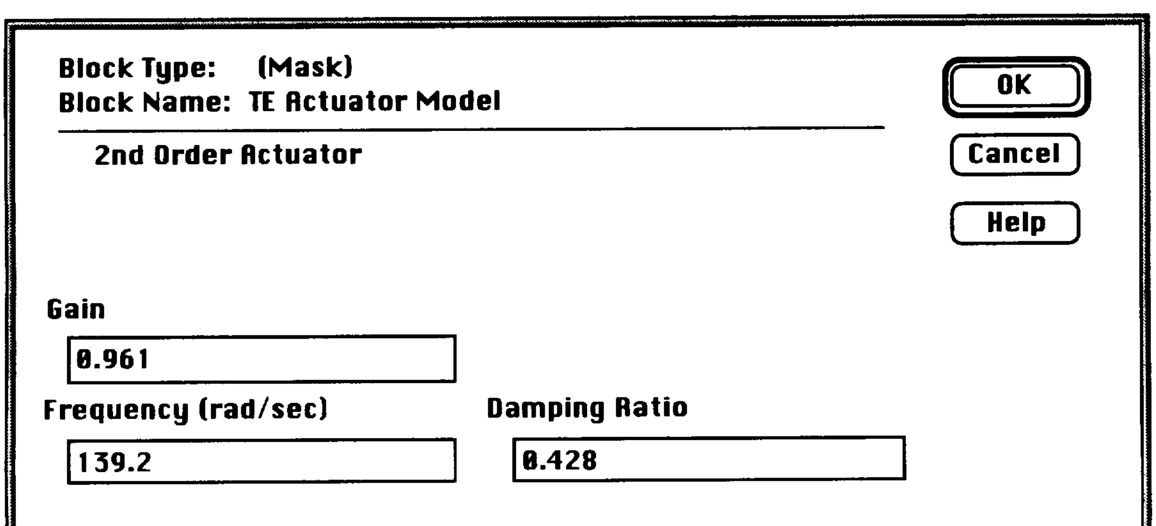

Figure 11 - Actuator EOM Block Dialog Box

Table 2 - Nominal Actuator Parameter Values

Actuator	Gain Value	Frequency (rad/sec)	Damping Ratio
Trailing Edge (TE)	0.961	139.2	0.428
Upper Spoiler (US)	1.115	125.65	0.683

4.3.2 Actuator Nonlinearities Subsystems

The actuator nonlinearities subsystems characterize the key nonlinearities of the BACT actuators – backlash, dead zone, position limits (saturation), and rate limits. Figure 12 shows the simulation diagram for the actuator nonlinearities.

Backlash describes the delay that occurs between the command and actual control surface deflection when the command changes sign. This is primarily due to "play" in the actuation mechanism between the hydraulic piston and the control surface itself. Deadzone characterizes the tendency for the control surface to need a minimum command to move away from zero deflection. This is partly due to the "wear" that occurs around the zero position of the control surface. The deflection of the control surface is zero until the command exceeds the deadzone value. Position limiting or saturation is associated with the maximum stroke of the actuator and limits the maximum control surface deflection that can be achieved regardless of the magnitude of the command signal. Rate limiting is associated with the fact that hydraulic fluid can only flow at a certain rate due to the supply pressure of the hydraulic pump and the size of the supply lines. Therefore, regardless of the magnitude of the control surface command the surface can move no faster than a specified rate. All of these effects are accounted for in the actuator nonlinearities subsystem.

It is important to note that the values that appear by default in each of the nonlinearity blocks are based on educated guesses and are not supported by any experimental data. The actual nonlinearities may be better or worse than described by the default values. Table 3 presents the default values for the trailing edge and upper spoiler actuators.

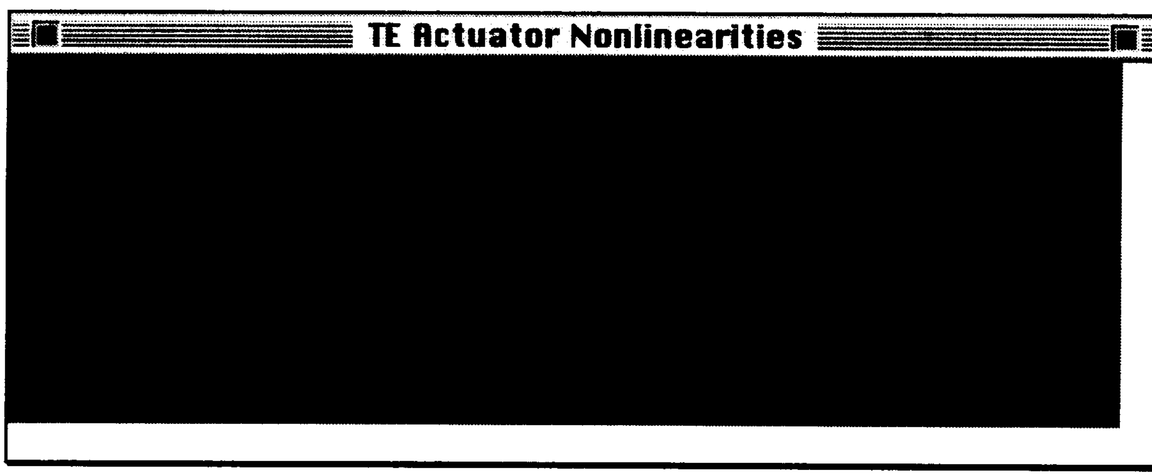

Figure 12 - Actuator Nonlinearities Subsystem Simulation Diagram

Table 3 - Nominal Actuator Nonlinearity Parameters

Actuator	Backlash (deg)	Dead Zone (deg)	Saturation (deg)	Rate Limit (deg/sec)
Trailing Edge (TE)	0.1	±0.1	±12	±250
Upper Spoiler (US)	0.2	±0.2	±12	±250

4.4 Turbulence Subsystem Diagram

The next subsystem block that appears in the main simulation diagram is the turbulence subsystem. The simulation diagram associated with this subsystem is shown in Figure 13. This system consists of a random number block, the turbulence model block, and two scopes.

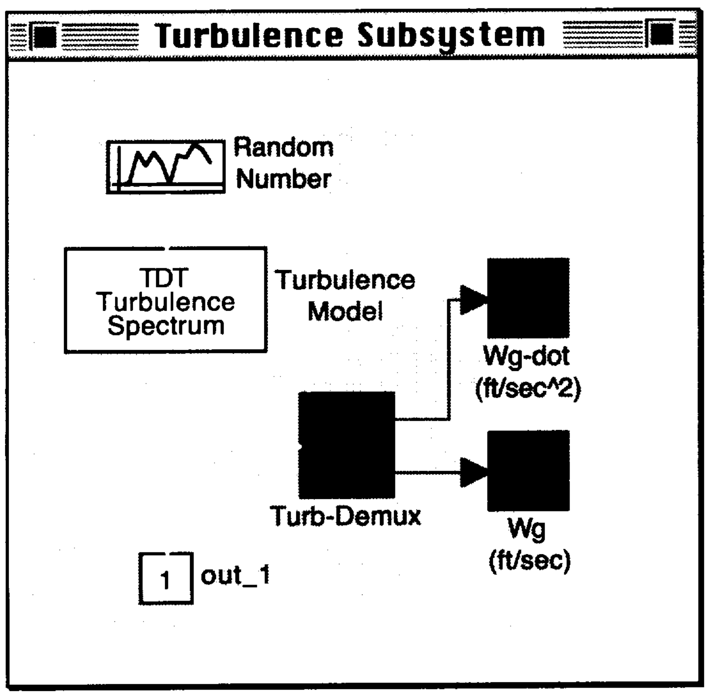

Figure 13 - Turbulence Subsystem Simulation Diagram

4.4.1 Random Number and Scope Blocks

The random number block generates a sequence of normally distributed unit variance random numbers that drives the turbulence model to produce vertical velocity disturbances that have a frequency spectrum very similar to the actual wind-tunnel turbulence. The user can specify the seed value to produce a repeatable disturbance sequence. The scope blocks allow the user to see graphical plots of the downwash velocity and acceleration produced by the turbulence model.

4.4.2 TDT Turbulence Spectrum Block

The turbulence model block is a masked block that executes the m-file BACT_Turb.m to generate a state space turbulence model depending on a user-specified reference speed. The model is based on the Dryden turbulence spectrum with parameters chosen to be representative of the Transonic Dynamics Tunnel

(TDT) in which the BACT system was tested.[11] There are only four admissible references speeds 100, 200, 300, and 400 feet per second. The value of 400 fps is preferred for flutter suppression controller studies since it most closely approximates the observed turbulence response of the BACT near the Mach 0.77 flutter condition. The reference speed is specified using the dialog shown in Figure 14.

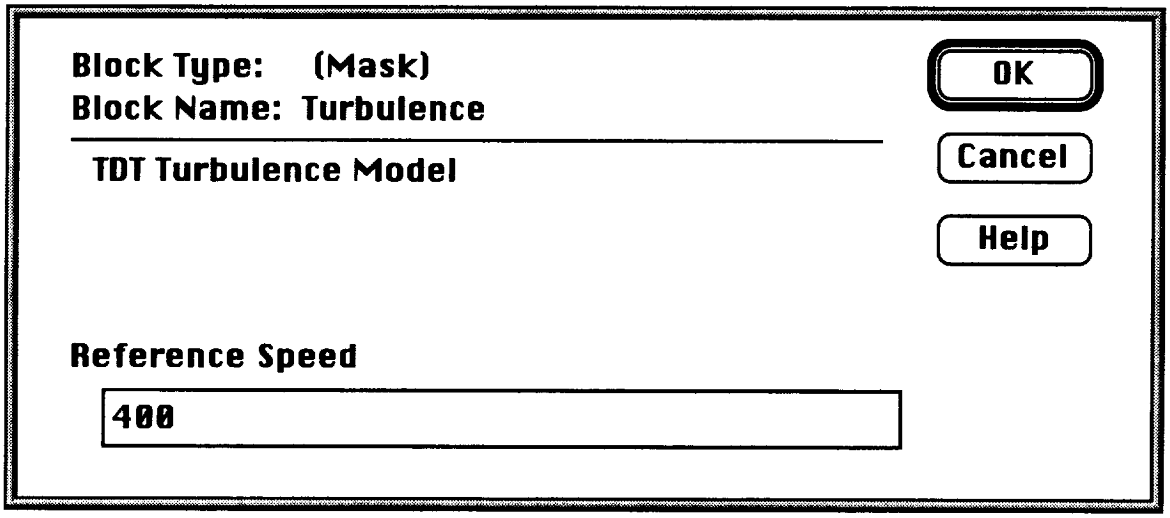

Figure 14 - Turbulence Spectrum Block Dialog Box

4.5 Controller Subsystem Diagram

The last subsystem block that appears in the main simulation diagram is the controller subsystem block. The simulation diagram of the controller subsystem is shown in Figure 15. The controller consists of transport delay and antialiasing blocks, Mux and Demux blocks, and the BACT FSS block.

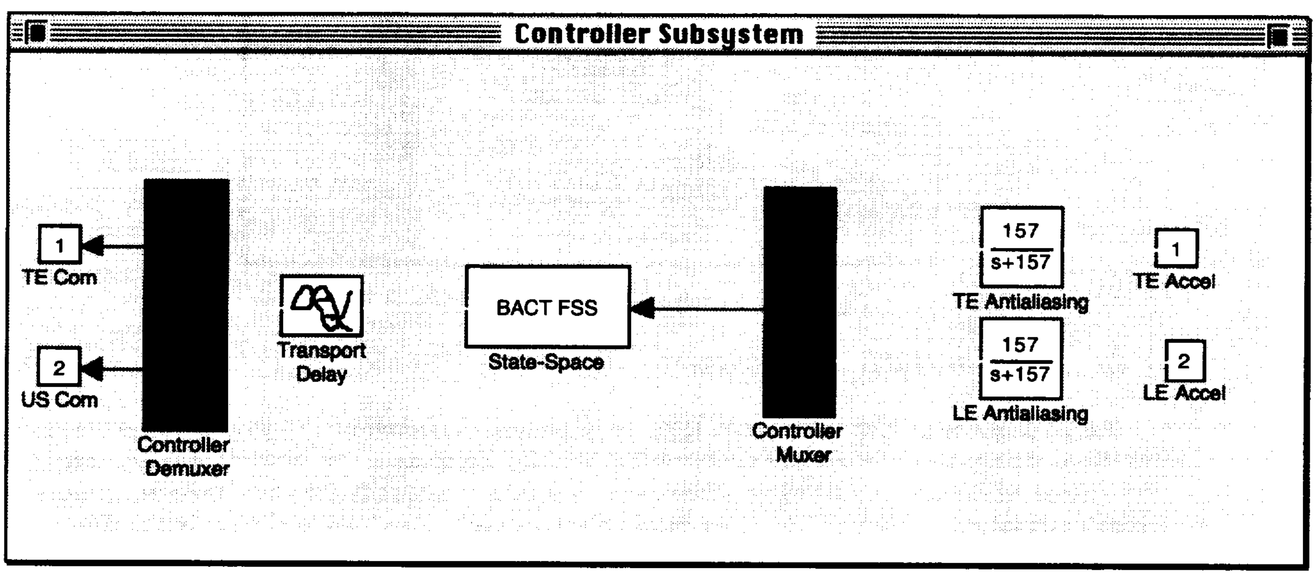

Figure 15 - Controller Subsystem Simulation Diagram

4.5.1 BACT FSS Block

The BACT flutter suppression system (FSS) block is a masked block that loads a MATLAB datafile from the current working directory or any directory on the MATLAB path list. The data file "Controller.mat" in the BACT Sim4Xport folder is used in the example dialog box shown in Figure 16.

The controller data file must consist of the four matrices of the continuous time state space representation of the control law. **The state space matrices must be named ac, bc, cc and dc.** In addition, the state space system must be two input, two output (though, of course, one of the columns of bc and or rows of cc and dc can be zero for single-input and/or single-output controllers). The two inputs must be trailing edge, TE, acceleration (g's) and leading edge, LE, acceleration (g's), respectively. The two outputs must be trailing edge command (deg) and upper spoiler command (deg), respectively.

model even though the actual BACT controller is implemented digitally. However, some effects of the digital implementation are accounted for in the transport delay and antialiasing filter blocks.

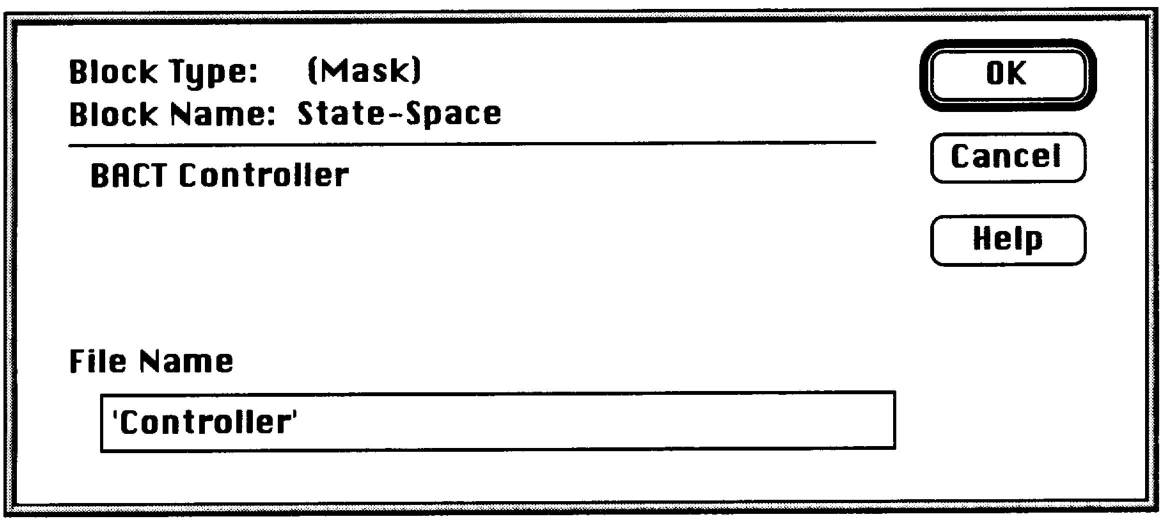

Figure 16 - BACT FSS Block Dialog Box

4.5.2 Transport Delay Block

The transport delay block is used to represent the computational delay inherent in the digital implementation of the control law in the control computer. The actual BACT system controller is implemented with a 200 Hz sample rate. Discretizing the control law introduces a pure time delay of approximately one to one and a half sample periods -- 0.005 to 0.0075 seconds. In order that the BACT simulation be somewhat conservative the transport delay is set to 0.0075 seconds.

4.5.3 Antialiasing Blocks

Since the actual BACT controller is implemented digitally, antialiasing filters are required to avoid aliasing of frequencies greater than 100 Hz. The filters implemented in the actual BACT system are of first order with a break frequency of 157 rad/sec (or 25 Hz). These filters provide approximately 12 dB of attenuation at the Nyquist frequency, 628 rad/sec (or 100 Hz).

5. Updates and Bug Fixes

Research using the BACT system is ongoing and there is potential for future updates to the BACT models and simulation. As updates are made they will be made available under a new version number.

The BACT simulation is being distributed for the use of anyone interested in the control of aeroelastic systems. Note that the BACT models and simulation are part of a research activity. Even though it has received extensive use there may still be errors and bugs lurking about. If any errors or bugs are found please report them to the author at the following address.

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6. Acknowledgments

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7. References

[1] Bennett. R.M.; Eckstrom, C.V.; et al..: The Benchmark Aeroelastic Models Program - Description and Highlights of Initial Results. NASA TM-104180, Dec. 1991.

[2] Durham, M.H.; Keller, D.F.; Bennett, R.M.; and Wieseman, C.D.: A Status Report on a Model for Benchmark Active Controls Testing. AIAA Paper No. 91-1011

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13. ABSTRACT *(Maximum 200 words)*

This report documents the structure and operation of a simulation model of the Benchmark Active Control Technology (BACT) Wind-Tunnel Model. The BACT system was designed, built, and tested at NASA Langley Research Center as part of the Benchmark Models Program and was developed to perform wind-tunnel experiments to obtain benchmark quality data to validate computational-fluid-dynamics and computational-aeroelasticity codes, to verify the accuracy of current aeroservoelasticity design and analysis tools, and to provide an active controls testbed for evaluating new and innovative control algorithms for flutter suppression and gust load alleviation. The BACT system has been especially valuable as a control system testbed.

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