ATTDES- An Expert System for Satellite Attitude Determination and Control, II

Donald. L. Mackison
Kevin Gifford

University of Colorado
Aerospace Engineering Sciences
Campus Box 429
Boulder, CO 80309-0429

(303) 492-6417
(303) 492-5514 (FAX)
mackison@spot.colorado.edu (e-mail)

Abstract

The design, analysis, and flight operations of satellite attitude determination and attitude control system (ADACS) require extensive mathematical formulations, optimization studies, and computer simulations. This is best done by an analyst with extensive education and experience. The development of programs such as ATTDES permit the use of advanced techniques by those with less experience. Typical tasks include the mission analysis to select stabilization and damping schemes, attitude determination sensors and algorithms, and control system designs to meet program requirements. ATTDES is a system that includes all of these activities, including high fidelity orbit environment models that can be used for preliminary analysis, parameter selection, stabilization schemes, the development of estimators and covariance analyses, and optimization, and can support ongoing orbit activities. The modification of existing simulations to model new configurations for these purposes can be an expensive, time consuming activity that becomes a pacing item in the development and operation of such new systems. The use of an integrated analysis tool such as ATTDES significantly reduces the effort and time required for these tasks.

Introduction

ATTDES consists of an extensive library of programs that covers much of these areas, and which is linked through a user driven system to model a wide range of configurations and to perform analyses. So that the

system may easily model a wide variety of satellites, the equations of motion are developed with generalized models. Whereas the formulation of dynamical equations of motion for simple spacecraft can be accomplished with essentially equal ease by means of any one of a number of methods, the task of formulating such equations for complex spacecraft can become prohibitively laborious unless a particularly effective method is employed. Kane, Roberson, Wittenburg and others have developed such methods. Through the use symbolic mathematics capability of MAPLE and the MATLAB Symbolic Math Toolbox, general equations of motion for very complex dynamic system can be developed by specifying symbolically the elements to be included in the equations of motion, including their alignment, location, and mass properties.

The software platform on which ATTDES is developed is the extremely popular MATLAB that is the present and foreseeable state-of-the-art in numerical computation as well as control design and simulation. With over 100,000 installed systems world-wide, MATLAB has become the standard high performance computing platform in control engineering and science. Because of the integrated nature of MATLAB, the evolution of ATTDES will include image processing and signal processing capabilities. Not only can such systems be modeled, but flight code can be generated quickly in standardized ANSI C. The use of MATLAB enables the system to run on all major computer platforms, including mainframes, workstations, and personal computers. Further, the complete MATLAB collection of toolboxes for Control Design, Robust Control Design, Optimization, Neural Networks is available for application to the satellite dynamic model in the workspace. By having the system cover a broad range of satellite configurations, the development of control laws for complex spacecraft will cease to be a pacing item in the development of new and unique attitude control systems. Rather, such analysis may be performed accurately and efficiently in a minimum amount of time. This system has been used to support design ADACS's for AXAF (Advanced X-Ray Astrophysical Facility), and for the STILLSAT (Staring, Imaging, Long-Look Satellite) and CUPS (Celestial Ultraviolet Photometric Survey) proposals to NASA/USRA.

Generalized architectures for equations of motion, together with the automatic generation of dynamic equations using the MAPLE symbolic manipulation capabilities through the MATLAB Symbolic Math Toolbox allow the inclusion of arbitrary structures such as flexible elements (i.e., the solar panels on the Hubble Space Telescope), angular momentum devices such as control moment gyros and momentum wheels, along with N2, hydrazine, and electric thrusters. Conventional attitude sensors such a Sun, Earth, and star sensors, as well as new technologies including Gravity Gradiometer and GPS sensors are easily included in the generalized attitude determination package. Advanced capabilities of ATTDES include extensive use of the image processing capabilities of MATLAB for visualization of stability and robustness information generated through the design process.

A common problem in the preliminary design of satellite attitude control systems and attitude determination systems is the generation of design data. One approach is to take the detailed simulation of the latest spacecraft design and modify it to match the new configuration. This can be an excruciating process, and often as not, does not lead to the desired result- a successful preliminary design analysis. Our objective here was to used Matlab in such a fashion that an inexperienced analyst could generate equations of motions for a variety of satellite configurations, specify a desired orbit, choose a stabilization scheme, linearize the equations of motion in a desired coordinate frame, design control gains, apply the control scheme to the linearized system, and finally, to generate a detailed nonlinear simulation including aerodynamic, gravity gradient, and radiation pressure effect.

Functions

It is intended that the progams in ATTDES will easily perform control system design, attitude determination, closed loop attitude determination/attitude control, and attitude covariance analysis. To this end, the principal function of ATTDES is the contruction of the equations of motion for the chosen satellite confiuration, and the generation of an appropriate linearization of the equation for control systems design, the development of attitude estimators, and covariance analysis studies.

Program Structure

The Matlab program consists of 50 programs run under a menu tree structure, selected by a menu utility (DOS version) or by push buttons and radio knobs (windows version). Data is entered into .dat files to create a model, or read from .dat files, modified, and stored in data files to modify the model. All data is passed through argument lists to each of the functions, and there is no common or global data throughout the system.
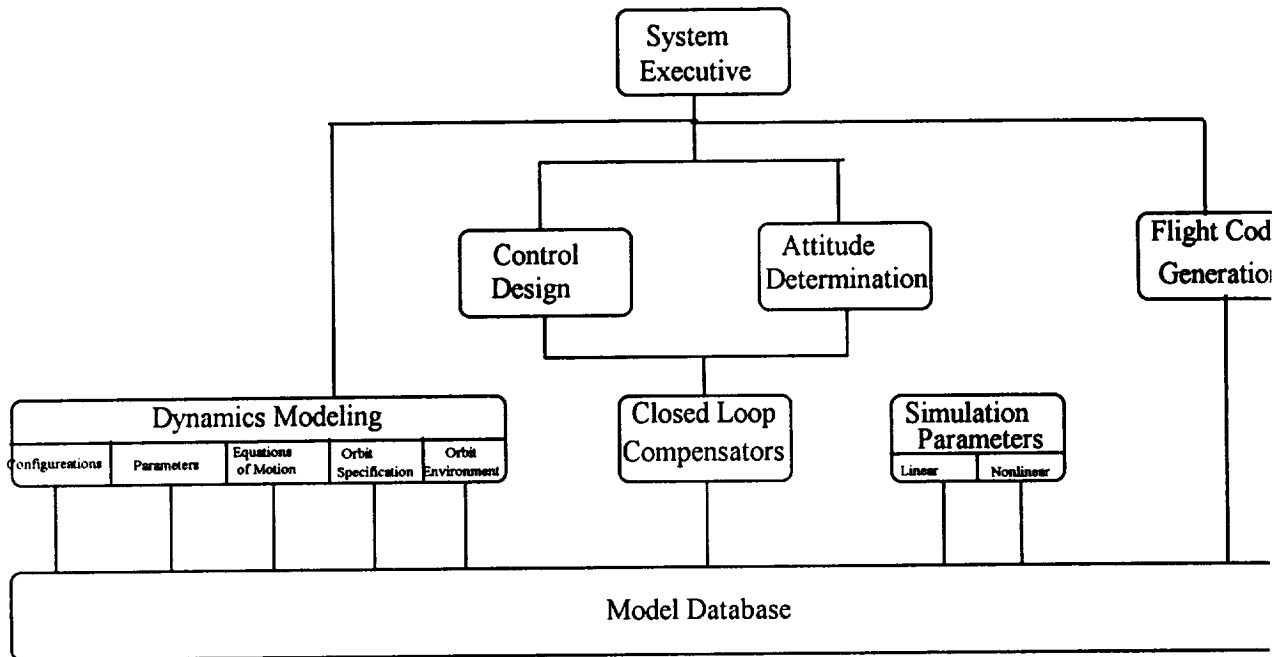
Figure 1: High Level Software Flow Diagram for the ATTDES System
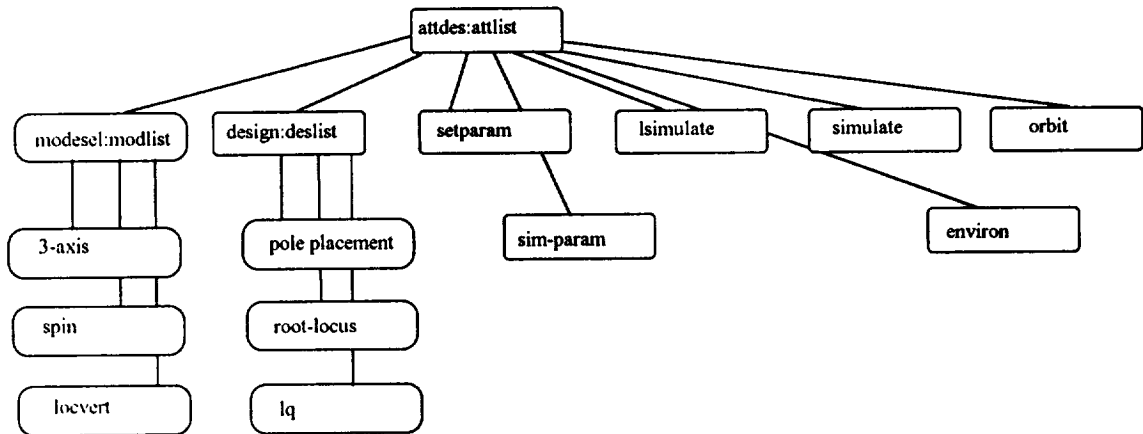

Figure 2: Detailed Flow for ATTDES System

ATTDES: Program executive

Modsel: Select mode of dynamics   (3-axis, spin, dual spin, gravity gradient, momentum bias

                  local vertical, etc.)

            Generate full nonlinear dynamic equations of motion for the configuration (Euler's

            equations for coupled bodies) and kinematic equations (quaternions)

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	Generate linearized equations of motion
Design:	Compute control gain- pole placement, root locus, lq, etc.
	Compute filter gains
Setparam	Set satellite physical parameters including mass and inertia, cross section for atmospheric and radiation pressure effects
Sim-param	Set simulation parameters- initial state vector, limits on integration
Lsimulate	Propagate the state vector using the state transition matrix.
Simulate	Integrate the full non-linear equation using a Runge-Kutta Felberg algorithm (rkf45)
Orbit	Select the satellite orbit, generate transformation from ECI to LV to Body frame.
Environ	Examine the magnetic, solar, and atmospheric environment over the orbit.

As each function of the program is exercised data is read from these data sets, new parameters computed, and saved into the appropriate data set.
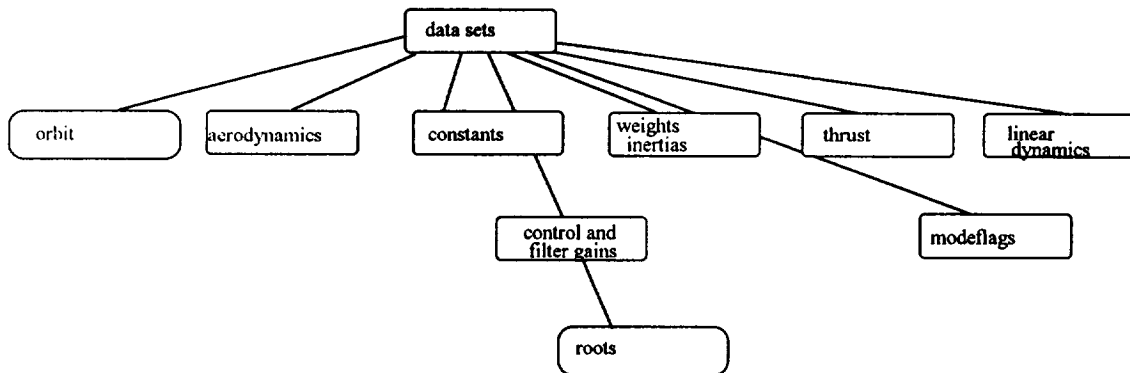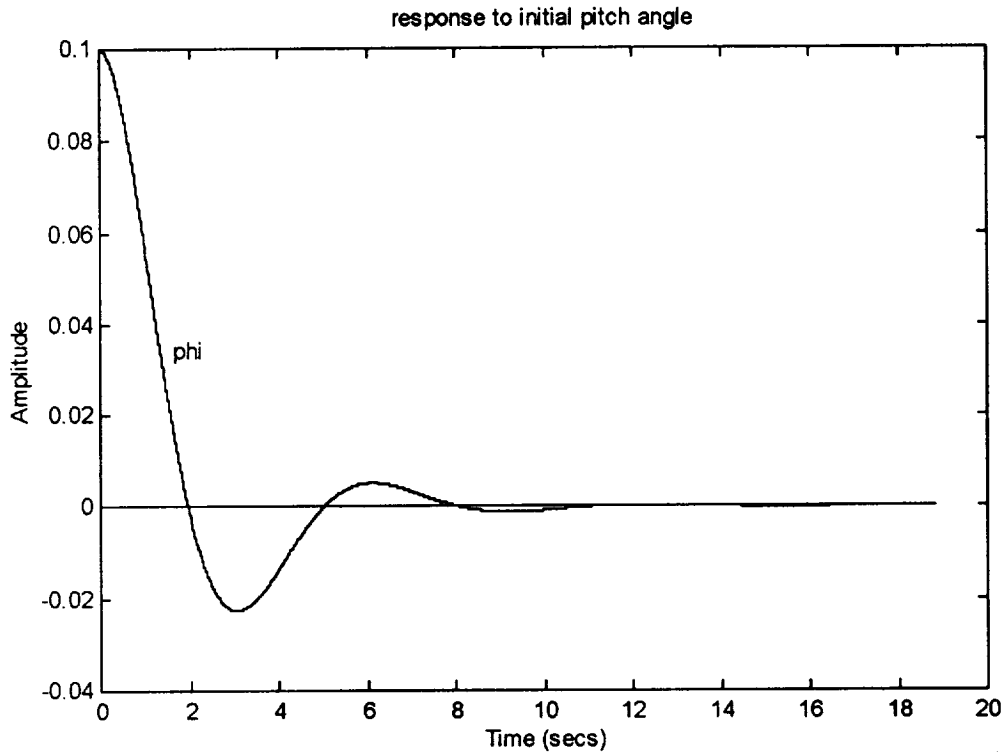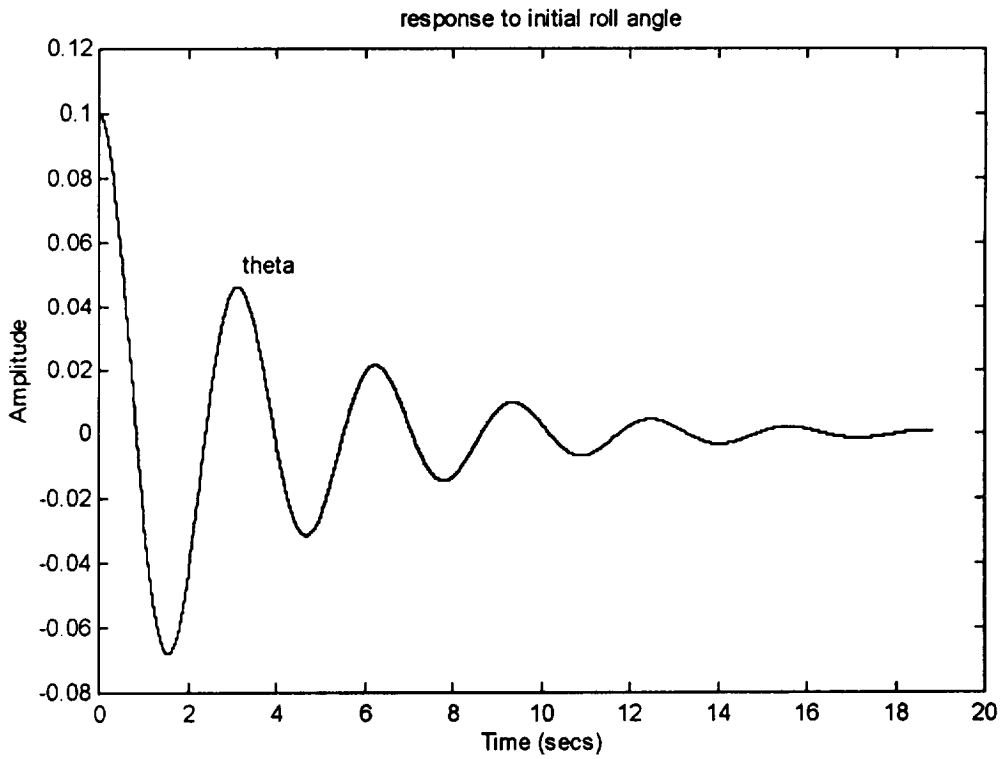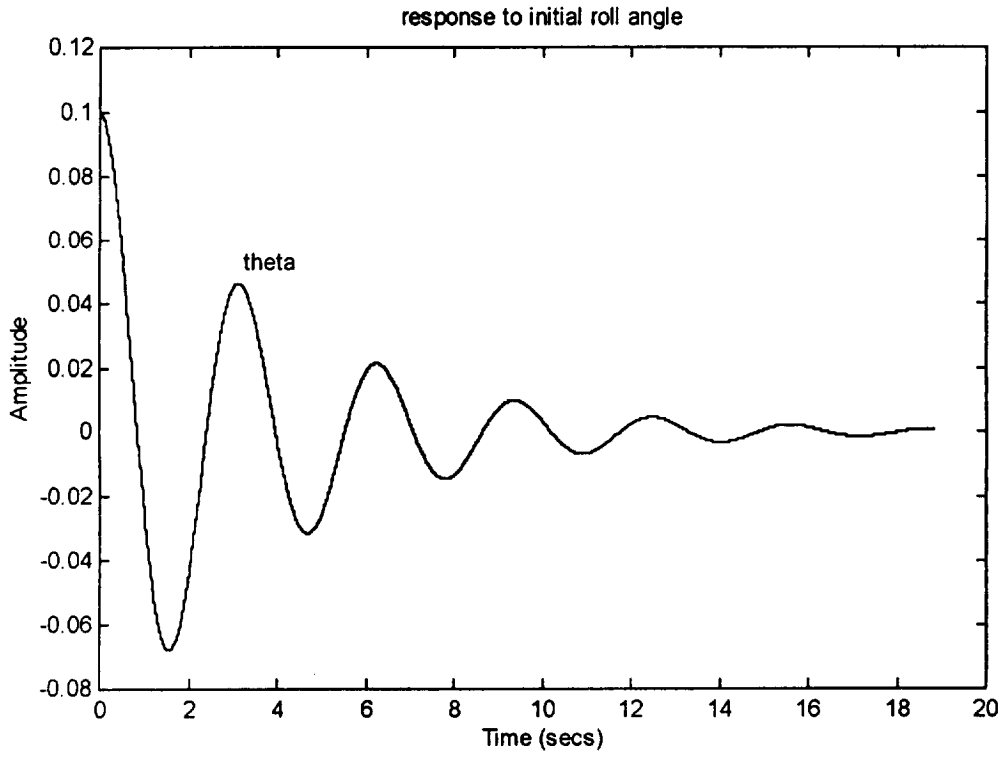

Because all of the dynamics and transformations between reference coordinate frames (ECI, LV, SC, Sensor, etc.) are available at all times in the system, ATTDES is equally applicable to satellite attitude determination problems. In order to accomplish this, sensor model files are available which include not only sensor geometry transformations (transformations from each sensor frame to the appropriate body reference frame) but also covariance matrices appropriate for each sensor. Therefore, within the basic ATTDES structure, one can perform attitude control studies, attitude determination and covariance analysis studies.
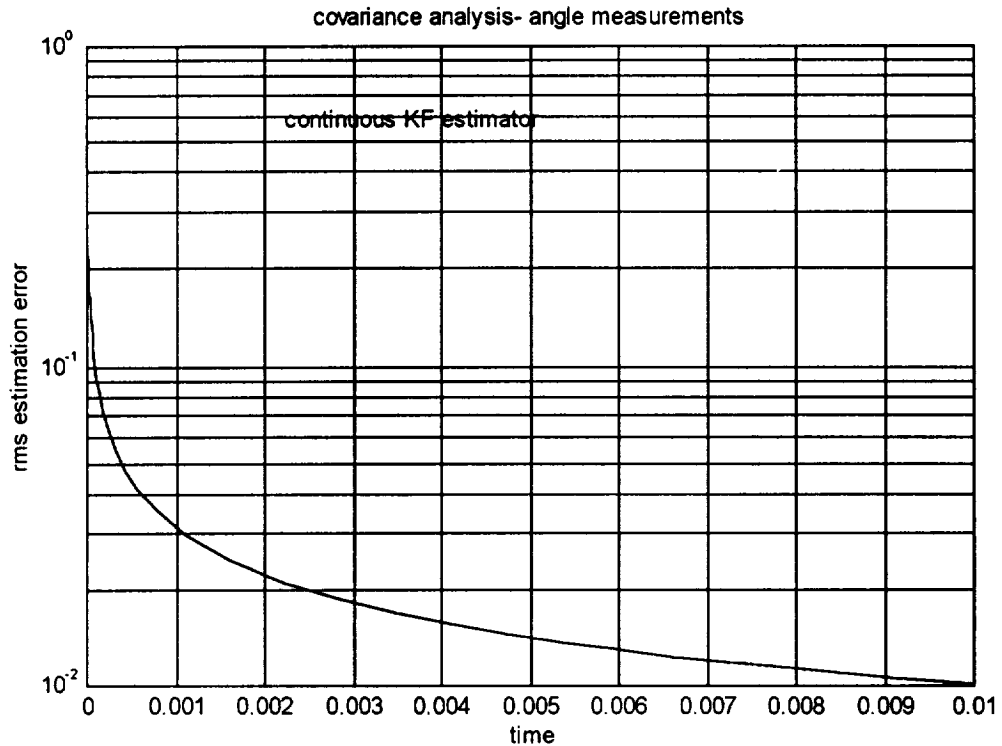
Example

For a simple example, we chose a gravity gradient stabilized satellite, with the control torques generated by small momentum wheels. The equations of motions are built into the system. We specify the control gains by using the linearized equations of motion and appropriate state and control weighting matrices to

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solve the Riccati equation, and then generate the simulation using the state transition matrix. Further, using sensor models, we can generate an appropriate estimator for the attitude- either for attitude determination, or to include as part of a closed loop attitude control system. We can also use the loop transmission recovery utilities to generate the closed loop controller.

response to initial pitch angle

response to initial roll angle

response to initial roll angle

Covariance vs. time

Ongoing Development

MATLAB has an extensive data visualization capability. Forthcoming features to be added to ATTDES using this capability include

- Attitude dynamics movies, based on the analysis data set, which shows a lighted, shaded figure rotating in the appropriate coordinate frame.

- Color graphics visualization of robustness information, which permits an intuitive understanding of the effects of parameter uncertainties, and singular vector surfaces which may indicate problems in parameter scaling and sensitivity for both control and estimation problems.

Conclusions

The use of Matlab for satellite attitude control system and satellite attitude design systems permits the analyst the use of high level numerical analysis software for performing design studies. Further, the use of the database capabilities of the system permits one to quickly modify a previous example, and to demonstrate the dynamic behavior of the closed loop system The inclusion of orbit models, very general attitude dynamics models, and sensor models will allow the support of a wide variety of satellite configuration.

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Appendix

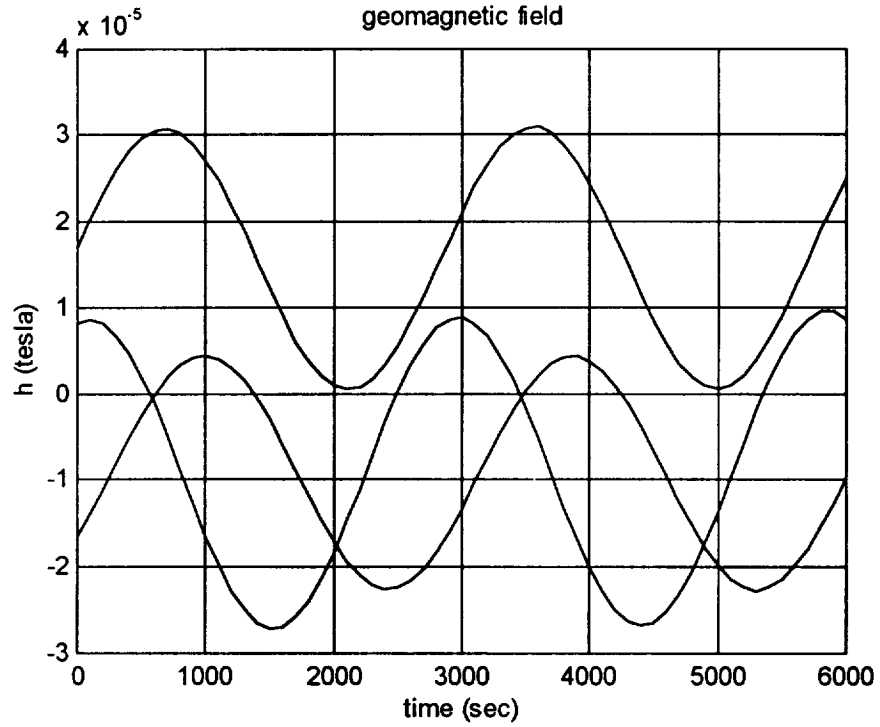Examples of Graphical Output for a Momentum Bias Satellite With Momentum Wheel Control

Figure 1. Geomagnetic Field Components Over An Orbit
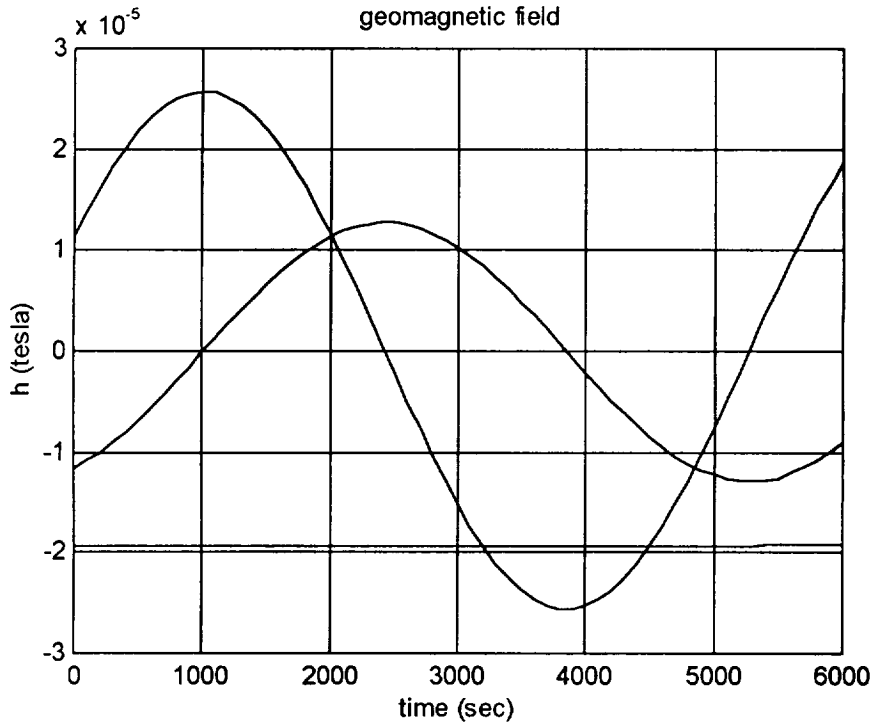Earth Centered Inertial Coordinates

Figure 2. Geomagnetic Field Components Over An Orbit-
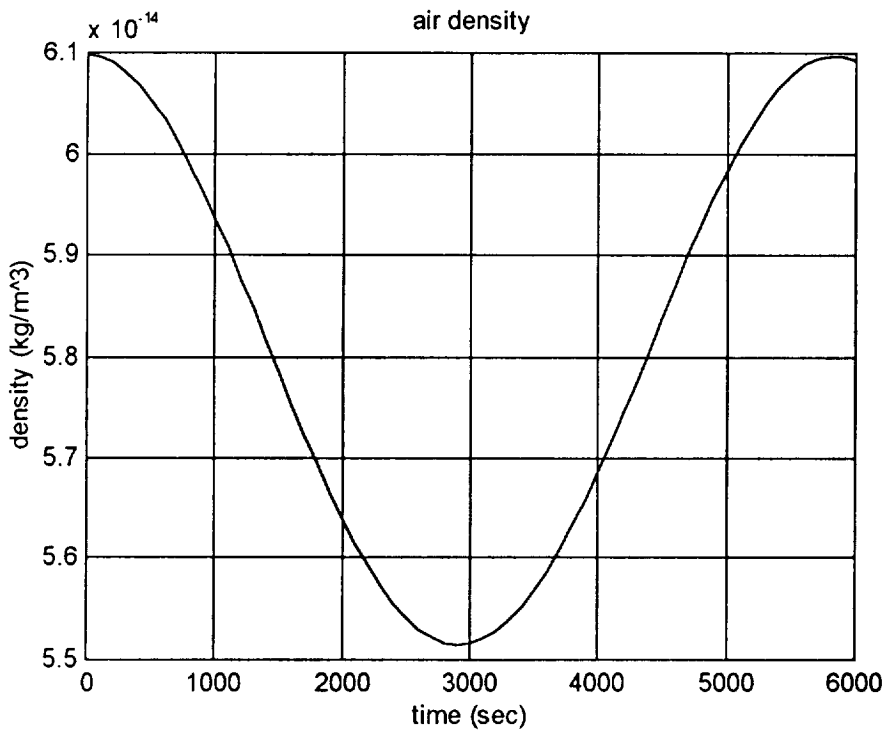Local Vertical Coordinates
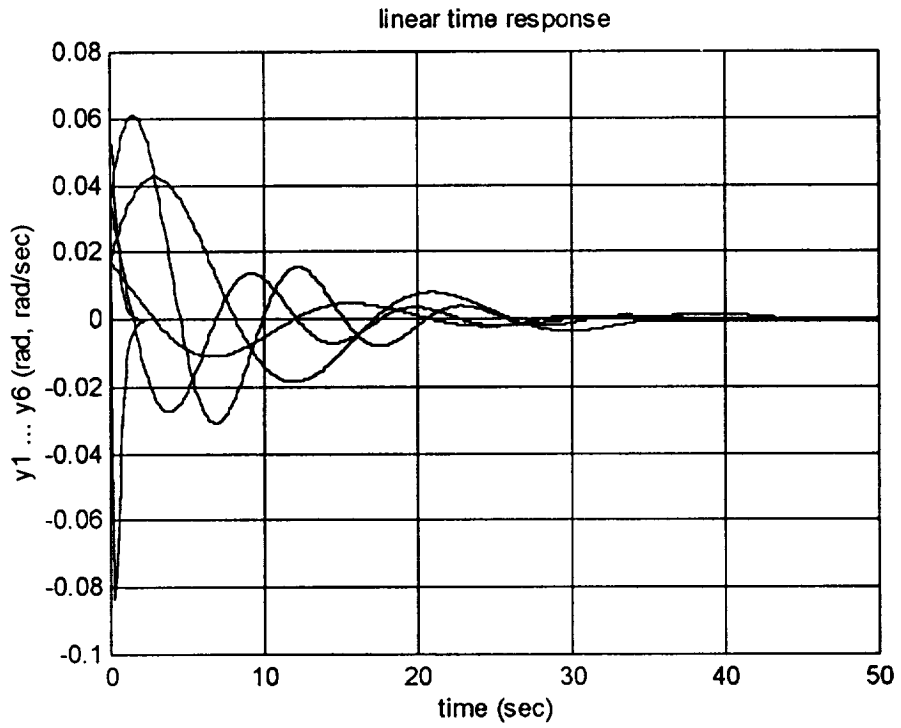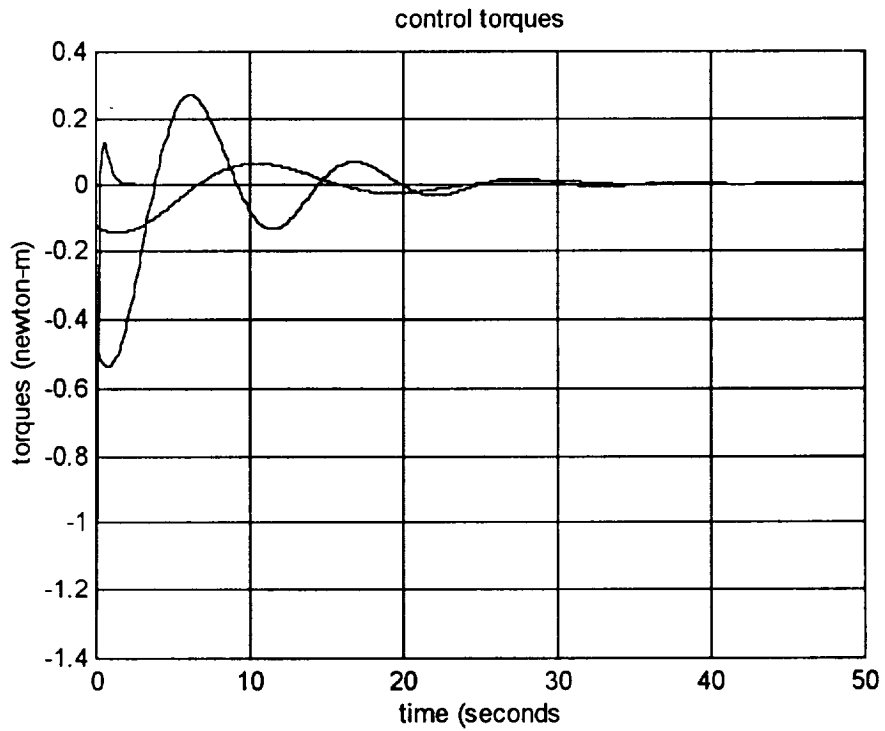

Figure 3. Air Density Over an Orbit

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Figure 4. Response From Non-Zero Initial Conditions

Figure 5. Control Torques

response to initial roll angle

response to random disturbance