# X-33 Attitude Control Using the XRS-2200 Linear Aerospike Engine

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## Abstract

The Vehicle Control Systems Team at Marshall Space Flight Center, Systems Dynamics Laboratory, Guidance and Control Systems Division is designing, under a cooperative agreement with Lockheed Martin Skunkworks, the Ascent, Transition, and Entry flight attitude control systems for the X-33 experimental vehicle. Test flights, while suborbital, will achieve sufficient altitudes and Mach numbers to test Single Stage To Orbit, Reusable Launch Vehicle technologies. Ascent flight control phase, the focus of this paper, begins at liftoff and ends at linear aerospike main engine cutoff (MECO). The X-33 attitude control system design is confronted by a myriad of design challenges: a short design cycle, the X-33 incremental test philosophy, the concurrent design philosophy chosen for the X-33 program, and the fact that the attitude control system design is, as usual, closely linked to many other subsystems and must deal with constraints and requirements from these subsystems. Additionally, however, and of special interest, the use of the linear aerospike engine is a departure from the gimballed engines traditionally used for thrust vector control (TVC) in launch vehicles and poses certain design challenges. This paper discusses the unique problem of designing the X-33 attitude control system with the linear aerospike engine, requirements development, modeling and analyses that verify the design.

## I. Introduction

The X-33 is an experimental vehicle, designed to test technologies that will be key in the development of a Reusable Launch Vehicle, or RLV, which eventually will replace the Space Shuttle as America's major vehicle for access to space. One strategy for next generation launch vehicles is the Single Stage to Orbit (SSTO) concept, which, as the name implies, does not rely on external boosters or fuel tanks to accomplish delivery of an orbital payload. One of the most significant pieces of the SSTO concept is the propulsion system, which must have a high installed thrust to weight ratio, and at the same time provide the necessary overall thrust as well as thrust vector control (TVC) for attitude maneuvers in both nominal and abort situations.

The propulsion system chosen for the X-33 uses two linear aerospike engines. Developed by BOEING, Rocketdyne Propulsion and Power Division, the aerospike engine was conceived in the 1960's. A prototype was built and hot fire tested, however, the design was considered too radical for the technologies and materials of the time. Since then, advances in materials, rocket engine components, engine controllers and flight computers have made the application of the linear aerospike feasible, and cost effective. This type of engine is ideally suited to the X-33 with its lifting body airframe. Lifting bodies typically have large base areas. The linear aerospike fills the base area, reducing drag. It is also integrated with the vehicle's structure, as no gimbal system is required, thus reducing installed weight. Another advantage of the aerospike engine is the fact that the combusted gases expand against the atmosphere on one side, and against a structure called a ramp on the other side as opposed to a conventional rocket

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engine with a bell shaped nozzle, that forces the gases to expand against the inside of the nozzle. A conventional engine nozzle is optimized for one atmospheric pressure (altitude) region where the engine will yield optimum performance, determined by the exit area of the nozzle. However, the plumes are allowed to expand against the atmosphere in the aerospike engine, so it compensates or adjusts to atmospheric pressure and will yield higher performance throughout the ascent phase of flight. The linear aerospike engine is discussed in more detail in section II.

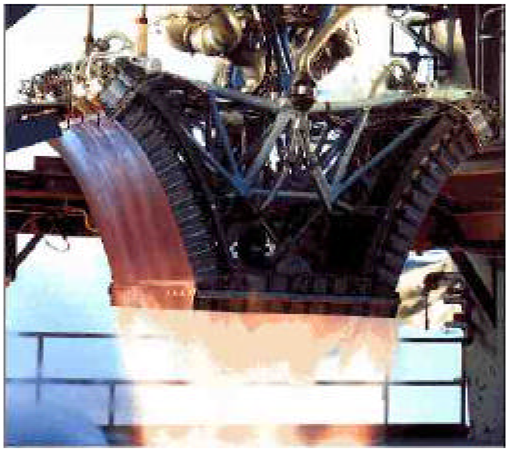

**Figure 1: Aerospike Hot Fire Test, circa 1970.**

In designing a vehicle and its attitude control system with this type of engine, a number of interesting, but not insurmountable challenges had to be overcome. Unlike conventional rocket engines with bell shaped nozzles and a gimbal system to achieve TVC, the aerospike engine accomplishes this by differentially throttling one bank of thrusters relative to another. Since the Ascent Flight Control System (AFCS) uses inertial euler angle steering commands, control derivatives that relate attitude angle to differential throttle commands for TVC had to be computed. Through CFD and other types of analyses, engine force and moment balances were obtained, allowing the construction of an engine database consisting of forces and moments as a function of power level, differential throttle setting, mixture ratio and altitude. These data were used along with trajectory data to obtain the control derivatives for the engine, compute control system gains, trim deflections and differential throttle settings which are used to evaluate control power requirements for a particular trajectory. A full, non-linear 6DOF simulation [3] is then used to verify flight performance. The two aerospike engines will be mounted in tandem as shown in figure 2. Certain constraints on maximum differential throttle between banks of thrusters, power level and mixture ratio are imposed so as not to exceed the engine's thermal and structural load limits. This led to a rather complex engine command limiting routine in the flight software that prevents commands from the AFCS from causing damage to the engines. Since no launch vehicle has flown with this type of engine, the interactions between the aerodynamics of the vehicle and the plumes of the engine are largely unknown. A five percent scale model of the X-33 lifting body and aerospike engine with working nozzles was used in wind tunnel tests to determine some of these effects in the subsonic regime. By ejecting cold gas through the nozzles in various combinations to simulate TVC, aerodynamic increments for the aerosurfaces were derived and added to the aerodynamic database. Other challenges involved modeling the sophisticated dynamic behavior of the engine itself and its interactions with the airframe. A non-linear model of the engine was developed by Rocketdyne in Matrix X [9]. The C code generated from this model is used in the high fidelity 6DOF flight simulation for controls, loads and thermal analysis with dispersions. A large degree of freedom (29,400 nodes) NASTRAN model of the airframe was used to determine engine - airframe interactions and identify high energy modes. These were included in stability analyses to determine flex filter coefficients and stability margins.

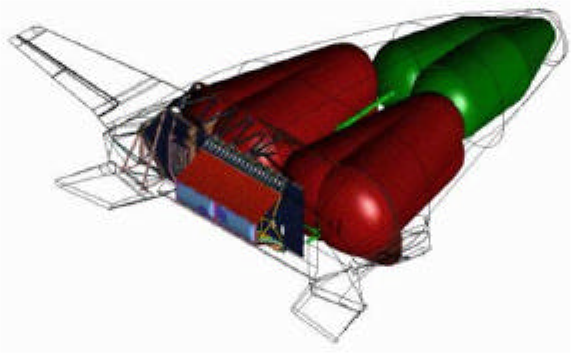

**Figure 2: X-33 Aerospike Engines and Fuel Tanks**

Flight tests of the X-33 are designed to test the propulsion system, lifting body airframe, thermal protection system, avionics, control actuators and other subsystems as experiments in SSTO technologies. However, in order to test these technologies to the extent that they are traceable to the RLV, which will fly to orbit, an incremental approach to the flight tests will be taken. The first flight will be a benign one. Later flights will stress the vehicle more, testing capabilities in all flight regimes from lift off at Edwards Air Force Base to Mach 9 and 180,000 feet altitude. The Space Shuttle and other launch vehicle trajectories are designed to a reference wind. If flight simulations indicate aerodynamic loading, MECO conditions, and other constraints can be met, then an approval is given for launch. If constraints can't be met, then a wind biased trajectory is used, that is, the winds are measured the day of launch, and the guidance commands are computed with a bias that compensates for the wind velocity. The X-33 trajectory design takes a slightly different approach. The trajectories are designed with a mean annual reference wind and are made to be within control margin criteria of 50% control power. In addition, Since staging is not necessary, the trajectory design and control system can be made simpler because they do not have to make provision for these events. The method of analysis used to evaluate these trajectories ensures that load and thermal limits are avoided, and other constraints are satisfied before flight. This includes stability and dispersion analyses with feedback to the trajectory designers, in case there is violation of a constraint that can only be solved by redesigning the trajectory. Rapid prototyping software has allowed automation of much of the procedure so that turnaround from trajectory design to flight is expeditious.

The X-33 flights will be completely autonomous, from liftoff to landing and roll-out. All guidance, navigation and control is contained in flight software on the dually redundant Vehicle Management Computer. The vehicle's position ,velocity and other states are supplied by Litton's LN-100G Inertial Navigation Unit with differential GPS. The attitude control system for ascent uses inertial roll, pitch and yaw angles and body rates along with guidance roll, pitch and  yaw steering, engine throttle and mixture ratio commands as inputs. Attitude control is effected by engine TVC and eight aerosurfaces, using electro-mechanical and electro-mechanical/pneumatic assisted actuators. The control law is classical, allowing well established analysis tools to be used that ensure a robust design with quick turnaround necessary for rapid prototyping and ease of implementation.

## II. The Linear Aerospike Engine

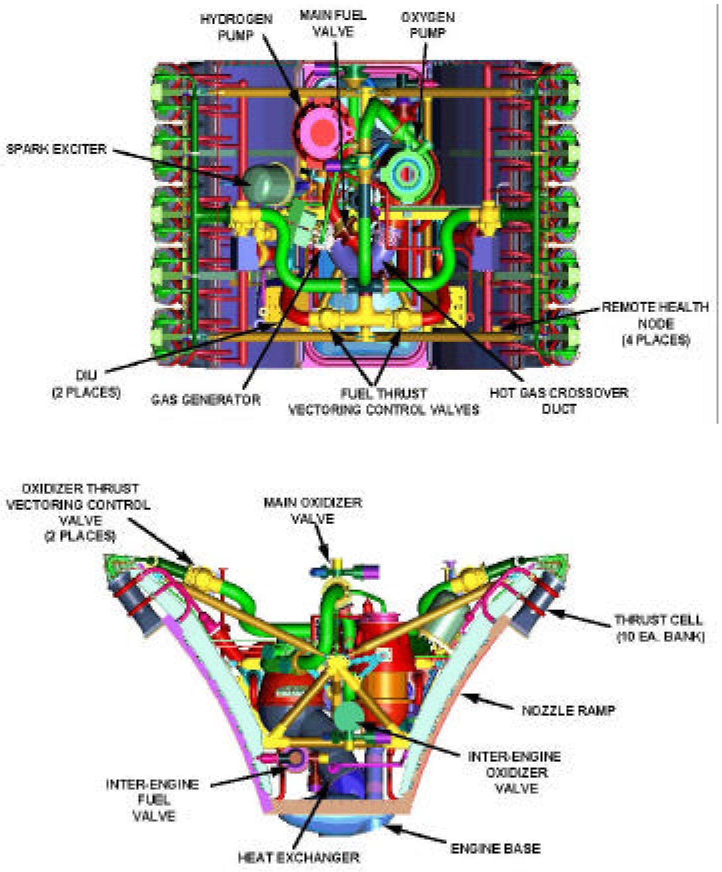

**Figure 3: Linear Aerospike Engine, Internal View.**

### Aerospike Engine Principle of Operation

Under nominal operation each of the two engines is powered by a Gas Generator (GG) power pack, whose function is to provide sufficient fuel and oxidizer to the engine system. Liquid Oxygen (LOX) and Hydrogen (LH2) are supplied to the Fuel and Oxidizer pumps at low pressure. The High Pressure Oxidizer Turbopump (HPOTP) and the High Pressure Fuel Turbopump (HPFTP), driven by the GG system deliver propellants to the chambers for the required chamber pressure (Pc).

To maximize the efficiency of the engine, the GG must run at the minimum possible flow rates to power the HPOTP and the HPFTP system so that the right amount of propellants at the right pressure reaches the combustion chambers. The amount of LOX and LH2 delivered to the GG system is regulated by two valves. These are the GG oxidizer (GGOV) and the GG fuel (GGFV) valves. A small amount of the oxidizer from the HPOTP, under high pressure, branches off to feed the GG and then flows into the combustion chambers of each bank. The total thrust per bank can be controlled with different settings of the two-oxidizer thrust vector control (TVC) valves (fig. 4). The latter regulate the supply of oxidizer to the chambers. Similarly, the fuel supply to the two banks of each engine is controlled by the two fuel TVC valves, with one difference. The fuel from the HPFTP feeds the GG system and then branches off to provide fuel to the thrust chambers. However, after going through the fuel TVC valves but before going into the thrust manifolds, part of the fuel flow is diverted to the nozzle ramps and the chamber housing cavities as a coolant, and then continues into the thrust manifold for combustion.

## X-33 Engine Control System Overview

The engine control system in the X-33 [10] is much more complex than that of the Space Shuttle Main Engine. This is because the attitude control of the vehicle needs engine thrust vector control (TVC) per bank to achieve the desired trajectories. This is accomplished with closed-loop control laws and open-loop table look-ups. The engine control system mainly consists of thrust level control (via the Pc) of each bank, mixture ratio (MR) control, TVC, and GG temperature control. Basically, a linear output feedback control system is utilized to control a highly nonlinear engine system. The principal nonlinear effects include: (i) nonlinear relations between valve input commands and pump, turbine and GG behavior under different conditions, (ii) nonlinear relations between valve positions, flow and resistance, among others.

The overall operating level of each engine is directly related to the GG system power level. This is closed-loop controlled via the GGOV. A table lookup, using thrust cell (TC) chamber Pc and engine MR, converts %-TC-chamber Pc and engine MR commands into the corresponding GG Pc. The GG Pc control system is closed-loop on measured values of the high-pressure fuel turbine (HPFT) inlet pressure sensor. Thus, the GGOV moves until the error between the measured and commanded inlet pressures is zero. The overall thrust level is a function of the available GG pressure. The latter provides sufficient flow through the turbines that power the pumps and allows them to generate the required chamber pressures. The overall thrust level of each bank is controlled by the LOX TVC valves.

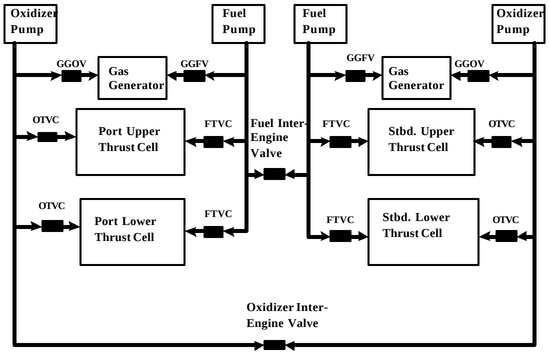

**Figure 4: Aerospike engine valve diagram.**

The control of MR for each engine is based on analytical predictions relating the MR to the fuel injector pressure (FIP), the fuel injector temperature (FIT), and Pc – all measured quantities. The calculated MR is then used as feedback for the closed-loop MR control system for each engine. This MR error is applied to the fuel TVC valve, which controls the fuel flow to each bank, until it is driven to zero error and the desired MR is achieved. The calculations of MR involve the computation of liquid oxygen (LOX) and GG flow rates. These are in turn computed from calculated fuel flow, Pc, and GG Pc.

The maximum TVC level achievable at any instant under nominal operation is 15% of maximum Pc. Under certain pre-defined conditions, the X-33 will reconfigure for the capability of carrying out up to 30% pitch commands. Moreover, in case one of the power packs fail, the vehicle will operate under the power pack out (PPO) condition, whereby only one GG system will provide the required thrust level. It will still be capable of performing 15% TVC and even 30% pitch maneuvers. The GG system chamber pressure is controlled via the GG oxygen valve based on closed-loop output feedback from the GG pressure sensor. The GG temperature is adjusted in an open-loop fashion based on a table-lookup that specifies the valve position for a given average Pc and MR commands.

The X-33 will be able to perform thrust vector control varying the thrust in each of the four banks of the two engine systems. The input commands to the engine are sent from the vehicle controller in the form of percent Pc and mixture ratio, ratio of oxygen to hydrogen, for each of the four banks (see figure 5). As the Pc amplitudes vary according to the bank thrust configurations shown in the figure, the thrust vector yaw, pitch, and roll forces are derived. Thus, pitch control is generated via differential thrust between the upper two banks and the lower two banks: yaw is between the two left and the two right banks, while roll torque (which is produced by opposing Z axis forces) is between the diagonally opposite banks. During nominal operating conditions, the two engines have independent control systems. There are two “inter-engine” valves that tie in the two engines under PPO condition, where one of the two Power Packs is shut down. This allows flow to both engines from a common power pack. Thus, the yaw control under nominal operation is implemented by throttling each engine individually for differential thrust. The actuation system is composed of electromechanical actuators with high response rates and with valves that have inherent dead band and hysteresis modeled into the dynamic equations representing their performance characteristics within the system simulation.

## III. Ascent Flight Control System

### X-33 Attitude Control System Description

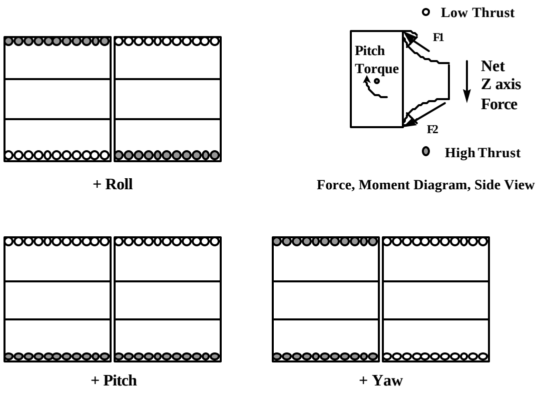

**Figure 5: TVC differential throttle combinations.**

The X-33 uses two linear aerospike engines with upper and lower banks of thrusters on each engine as depicted in figure 5. Unlike conventional launch vehicles, however, TVC is accomplished by differentially throttling the upper and lower banks of thrusters for pitch and roll, and differentially throttling the left and right engines (both upper and lower banks) for yaw. Open loop throttle commands modulate total engine thrust and are received from the Guidance function. Closed loop mixture ratio commands, that ensure that all propellants are depleted, are received from the Propellant Utilization function. These last two quantities are not used in the control law itself, but are used in limiting the engine commands. In addition to the engines, eight aerosurfaces are used for attitude control; four elevons, two flaps and two rudders, as shown in figure 6. Input to the control law are body errors formed by the product of the inertial to desired body quaternion, received from Guidance, and the “sensed” inertial to body quaternion. Similarly, body rate errors are formed from commanded and sensed body rates. These are used in the Variable Structure Proportional Integral Derivative (VSPID) control law, which outputs roll, pitch and yaw torque commands.

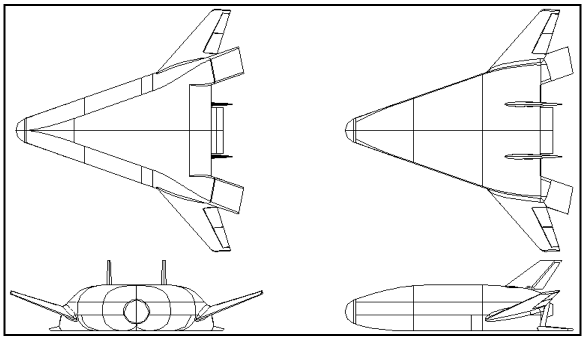

**Figure 6: X-33 Aerosurface Configuration.**

A PID control law was chosen based upon performance in existing launch vehicles, and from performance in past SSTO-RLV concept studies [1][2]. The controller is easily tuned to provide good transient response with zero steady state error using a variety of gain computation methods that can be based simply on control torques, inertias, desired crossover frequencies and damping. VSPID, shown for an arbitrary attitude channel in figure 7, is an innnovative way of using PID control with limiting, in this case, the output torque command. During saturation, the integral path is switched to an alternate one that forces the signal to the edge of saturation, preventing integral wind-up. This design has been benchmarked against several other methods of integral wind-up prevention, and was shown to be superior in decreasing the amount of time spent in saturation and in transient response [6].

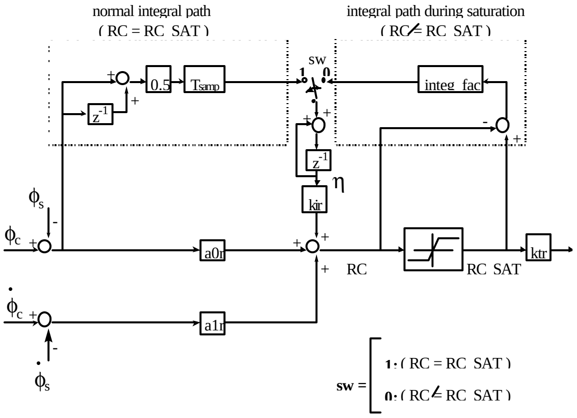

**Figure 7: VSPID Control Law**

The AFCS consists of four major parts; 1) error processing, 2) the control law, 3) control allocation and 4) mixing and engine command processing. Control system synthesis in this way, with torque commands as output, allows the designer to choose whatever control law is needed independent of the control allocation problem so that the two can be worked concurrently, and different designs may be interchanged. The control allocation method chosen minimizes the control deflections while satisfying the three axis control torque requirements[3]. The control system gains, and control allocation gains are stored in the Vehicle Management Computer as tables and are scheduled as a function of velocity. A high level block diagram of the AFCS is shown in figure 8.

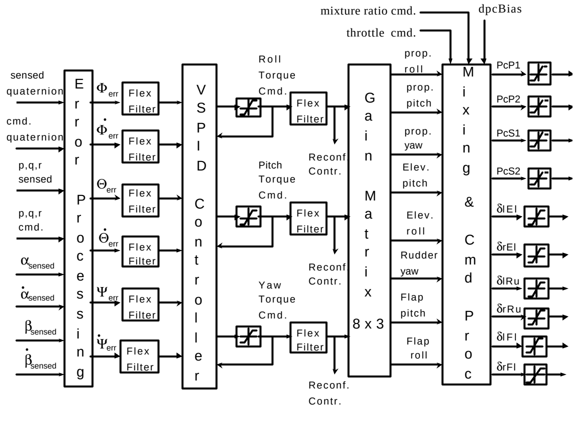

**Figure 8: X-33 Ascent Attitude Control system**

Provision for load relief is made by using sensed angles of attack , side slip, and their derivatives, to compute attitude error augmentation signals that allow the vehicle to “weathercock” into the wind, reducing aerodynamic loads. This feature is reserved for only severe wind conditions, however, and is intended to increase launch probability. Provision is also made to supply the torque commands to a reconfigurable control system [5] in the event of an aerosurface actuator failure. In the event of a single engine failure (PPO), the nominal control system is used, but with alternate sets of gains. To compensate for the disturbance torque from the engine’s longitudinal thrust component and the the vehicle’s center of gravity, a pitch attitude bias command may be input open loop into the mixing and command processing function, to eliminate pitch attitude transients during liftoff.

## Control System Requirements

Due to the shape of the lifting body fuselage, complex tank structures were required that could accommodate the aeroshell, the payload bay and the load paths from the thrust structure. There are two liquid hydrogen tanks located aft in the vehicle, and one liquid oxygen tank located in the nose, as shown in figure 2. Extensive analysis was required to derive the degree of propellant damping required to provide attitude control stability during ascent for all missions. This was one of the most important control system requirements for stability, because the propellant slosh mass, that mass which contributes to slosh dynamics, can be as high as 18% of the total vehicle mass. For this vehicle, the slosh damping analyses were supplemented by tests at Marshall Space Flight Center on subscale X-33 tank sections, which yeilded slosh masses, slosh mass locations, and natural frequencies. The damping requirements from the analyses were used in designing ring type slosh baffles.

In the early phases of X-33 design, allocations for gain and phase margins were made for actuators, transport lag and flex filtering before the dynamics from these were known. This was based upon the estimated gain and phase characteristics from the various subsytems. A gain margin requirement of -

6db (high frequency) and +6db (low frequency) and a phase margin requirement of 30 degrees was chosen for the attitude control system, including vehicle and subsytem dynamics, to ensure sufficient margin that would accommodate errors in modeling, disturbances, and hardware constraints that could not be forseen. From analysis concurrent with the subsytems that were still being designed, and from past experience with launch vehicle subsytems, the dynamic requirements for these subsystems were derived.

## Stability Analysis

In the first phase of the stability analysis, control power, an estimate of the aerosurface deflections and engine TVC commands that are required to trim the vehicle are calculated. This begins with selecting operating points from a three degree of freedom analysis of the trajectory for a particular mission. For X-33, each mission's objectives are different. As a result, the operating conditions, particularly engine throttle profiles and angles of attack and sideslip, can be significantly different among each mission and will require a stability analysis for each one. Operating points are chosen judiciously, ensuring regions of flight where loads are maximum, where thrust changes rapidly and where slosh damping is at a minimum are analyzed. Control system gains are also calculated during this phase, and if control power constraints are met, then the analysis advances to the next one; frequency response analysis. Occasionally, control power requirements are not met, and a slight adjustment to the trajectory design will be necessary.

The frequency response analysis, like the first phase of the stability analysis that assesses control power, is largely automated. The gain calculations, and the inherent robustness of the VSPID controller coupled with the Optimal Control Allocation algorithm that is used to derive the elements in the control allocation matrix, provide a very reliable control system that usually satisfies the stability margin requirements at all operating points. The frequency responses are calculated in batch mode for all axes and all operating points, then checked for margin violations afterwards. If a margin requirement is violated, usually adjustment of a forward loop gain will remedy the problem. These are always numerically small changes that do not adversely affect transient or steady state response. The frequency responses are calculated from the input to the control allocation matrix to the output of the controller; i.e., open loop at the torque command (see figure 8). Linear and non-linear models are programmed into the Marsyas/Octave environment [4]. Marsyas is capable of linearizing the models and generating A, B, C, D matrices for analysis. Numerous controls analysis tools including frequency response, eigenvalue analysis, and root locus are built in. In modelling some subsystems, like the linear aerospike engine with its highly nonlinear dynamics, it is more efficient to obtain frequency responses from fast Fourier transform analysis of the time responses. This was done for various engine operating conditions that envelope those conditions that would be encountered in most flights. From this frequency response data, system identification techniques [7] were used that provided continuous polynomial transfer functions that were used to approximate the engine responses in the linear models used for stability analyses. Figure 9 shows a typical frequency response of the attitude control system in the pitch channel. The gain-phase plot shows the rigid body response overlain with other curves depicting how the frequency response changes with the addition of each modelled effect.

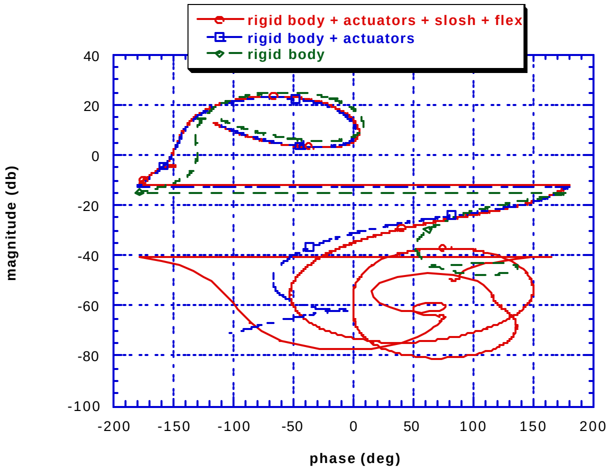

**Figure 9: Typical Pitch Frequency Response.**

Engine actuator dynamics decrease gain and phase margins significantly, however, the control system gains, which are based upon rigid body with propellant slosh eigenvalues, provide enough margin in the critical frequency range. Slosh modes are phase stabilized by passive damping provided by ring baffles in the LOX tank. Flex body effects are gain stabilized via digital notch filters. Some gain and phase margin is decreased by flex filtering in the AFCS, and by an anti-aliasing filter in the Inertial Navigation Unit. Most of the flex dynamics are high frequency for this flight condition, as can be seen in the figure.

## IV. Ascent Flight Simulations

The high fidelity six degree-of-freedom (6DOF) flight simulation used for X-33 was developed at Marshall Space Flight Center for the X-33 project, but was intended for modeling and analysis of any vehicle requiring ascent, orbit or landing studies. The program, called MAVERIC (Marshall Aerospace VEhicle Representation In C), is capable of simulating X-33 or RLV flights in 3DOF or 6DOF from liftoff to landing. The main program and most subroutines are in C, but also included are FORTRAN subroutines written by different designers of the X-33 subsystems .

Two engine models may be used in the flight simulations; a simple table lookup model and a non-linear model autocoded from the Matrix X program used for stand alone engine analyses. The former is used for Monte Carlo analyses requiring large numbers of simulations, and the latter is used for more in depth studies of selected cases where it is desired to know details such as throttle rates, limit cycling, hysteresis, dead band and the effect these have on attitude control. This model, called the GG-Yaw-PPO model (Gas Generator Yaw, with Power Pack Out modeling), includes the engine control systems, Real Time Propulsion Model [9], actuators (valves) and sensors for both engines. It also transforms the calculated Pc into forces and moments in the engine frame. The GG-Yaw-PPO model calculates pressures, flow rates, temperatures, pump speeds and valve positions with associated non-linearities. Inputs to the model are Pc commands to the upper and lower banks of thrusters, MR, ambient pressure and flags and parameters that indicate modes of operation such as 15% or 30% differential throttle and PPO. Many outputs may be selected, but the ones used primarily in MAVERIC are actual Pc, actual MR, thrust, forces and moments. Under nominal operation, the Inter-Engine Valves (IEV) are closed. For PPO, the IEV's open while the failed engine is being shut down. Simultaneously, the good power pack throttles up to compensate for the loss in thrust. The GG-Yaw-PPO model was compared with engine thrust cell test [8] results and was fine tuned to represent more closely the actual hardware.

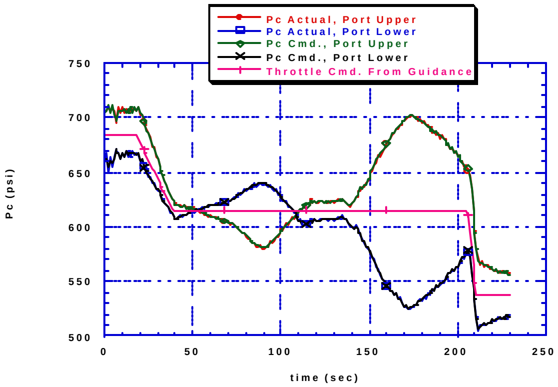

**Figure 10a: Port Engine Pc and Throttle Response.**

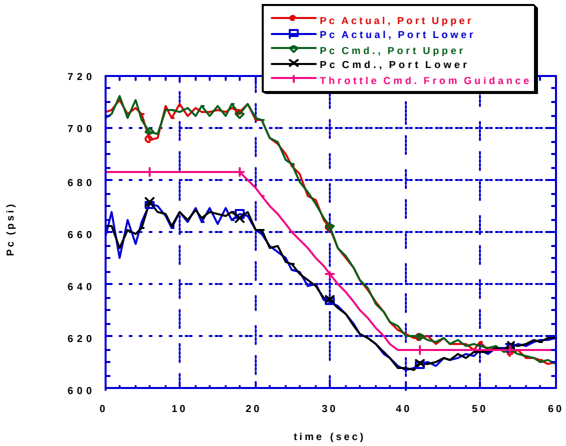

**Figure 10b: Port Engine Pc and Throttle responses, enlarged.**

Figure 10 shows plots of Pc commands for the port engine from a nominal ascent simulation using the GG-Yaw-PPO engine model. Each plot shows curves of the commanded Pc's overlain with the actual Pc's. The throttle commands, engine throttle required by guidance to fly the desired trajectory, are also plotted. The Pc commands for the upper and lower banks are offset from the throttle command indicating pitch attitude error compensation is being commanded by the AFCS. Most of the attitude control requirement is in pitch due to an initial offset between the thrust vector and the vehicle center of gravity, and also due to increased angle of attack later in the trajectory. The actual Pc's track the commands very well throughout the flight. Some oscillation may be seen about the steady state due to engine non-linearities, i.e., deadbands in the TVC valve positions.

Large numbers of dispersion simulations were run Monte Carlo fashion, based upon a 95% probability of success with a 90% confidence level (2 σ). A maximum TVC limit of ± 15% differential throttle was imposed for all dispersion simulations. Vehicle and environment dispersions were considered. Vehicle dispersions included mass properties, aerodynamics, actuators and propulsion system, among others. Environment dispersions included winds, atmospheric density, pressure, temperature and the speed of sound. Propulsion system dispersions included thrust, mounting location and angle, MR, and thrust mismatch between the two engines. Figures 11 through 18 show simulation results for the most severe of these dispersions. The curves represent the envelope, maximum and minimum at each time point, from a set of about 300 simulations. Also shown, are curves of the nominal time history for each variable. Wind magnitude peaked at nearly 450 ft/sec (fig. 11), however aerodynamic loads were kept quite low (figs. 12, 13). Ground tracks (fig. 14) deviated very little from nominal, ensuring a high probability of alignment with the landing site. Thrust excursion (fig. 15) from the nominal was a result of propulsion sytem and environment disersions. The attitude errors (figs. 16, 17, 18) are reasonable for such flight conditions. The pitch error maximum got quite large near 200 seconds as a result of negative Q-Alpha loads in this region, however all errors are driven close to zero by MECO ensuring safe handover to transition and entry control.

## V. Conclusion

The quality of the AFCS design with the XRS-2200 linear aerospike engine is evident in the simulation results. The total attitude control system is robust to dispersions, ensuring a high probability of successful flight from liftoff to landing. Current enhancement efforts include further automation of the design cycle process that will expedite flight data loads, which include AFCS gains, whenever a new mission is presented. Also planned is more flight control analysis using the GG-Yaw-PPO model in 30% TVC mode. In addition, a gain scheduling scheme is proposed for the aerospike engine control system, that would provide improved response over a wider range of operating conditions.

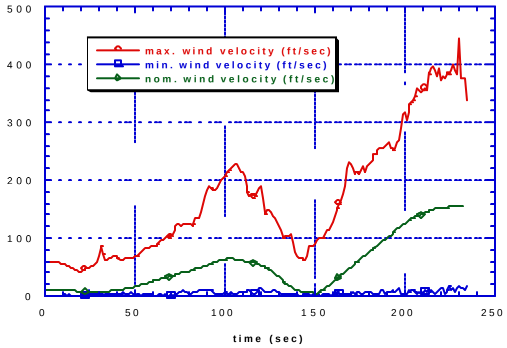

Figure 11: Wind Velocities.

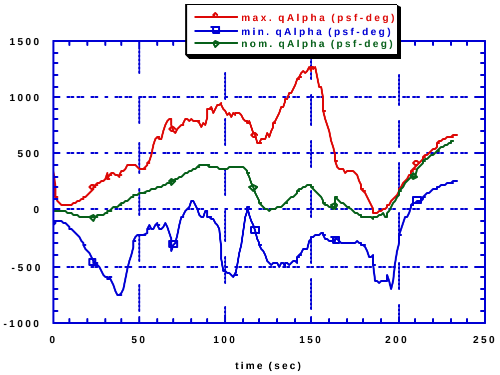

Figure 12: Q-Alpha.

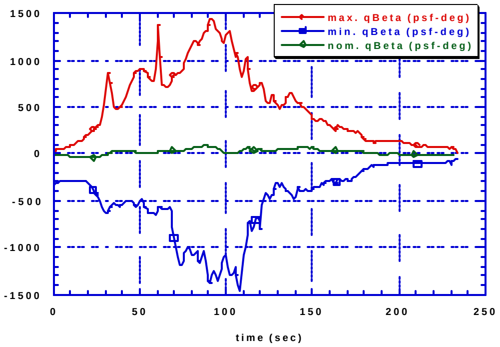

Figure 13: Q-Beta.

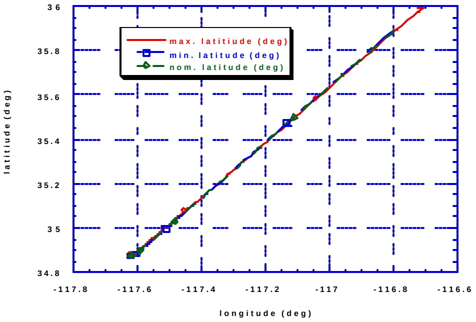

Figure 14: Ground Tracks.

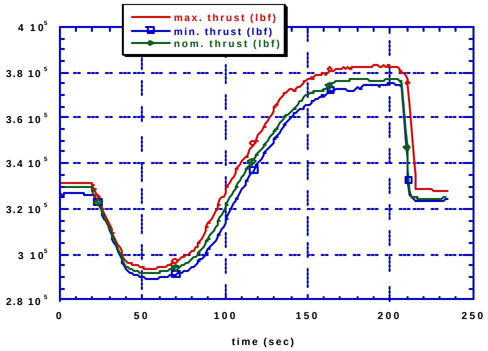

Figure 15: Total Thrust.

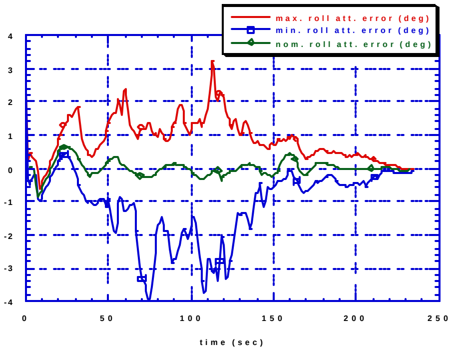

Figure 16: Roll Attitude Error.

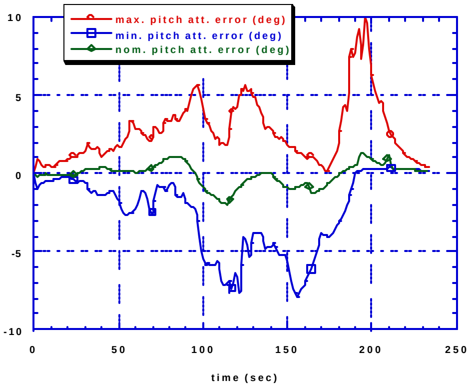

Figure 17. Pitch Attitude Error.

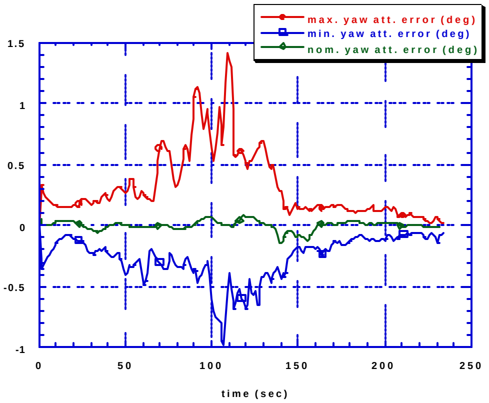

Figure 18. Yaw Attitude Error.

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