AEROSPIKE ENGINE CONTROL SYSTEM FEATURES AND PERFORMANCE

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ABSTRACT. Results of the control system design and analysis of the Aerospike engine are presented herein. Also presented is a brief history of rocket engine control systems, the novel features of the Aerospike engine and its characteristic challenges. The Real-Time Engine Model (RTEM) and the actuation system model are briefly overviewed and the analytical aspects of the simulation are underlined. The main control system features, thrust vectoring logic, and analytical approaches used in the design process are presented and discussed. Some simulation results and analytical trade off studies are also presented and compared to recent test results. Conclusions and recommendations are drawn.

1. INTRODUCTION

The linear Aerospike engine uses an external expansion nozzle, whereby one side of the supersonic expansion is a center body or a “plug,” while the other side is a free streamline [1]. This free streamline results in a performance advantage for the rocket engine, thus rendering its operability in both deep space and within the atmosphere as a single-stage launch vehicle[2]. As the vehicle ascends into higher altitudes, the ambient air pressure is reduced; the exhaust expands further, unlike conventional rocket engines, where the high area-ratio bell nozzle can expand the exhaust to pressures lower than the surrounding atmosphere. The feature that allows altitude compensation of the plug nozzle results in higher nozzle area ratios providing higher performance for the X-33 vehicle and better thrust-to-weight ratio that the SSME (Fig. 1).

The altitude compensation feature and thrust vector control is provided under minimum requirements for geometric variations and no gimbaling of the nozzle and are the main discriminating features of the Aerospike engine. There will be two Aerospike engines at the aft end of the X-33 vehicle (as shown in the figure) with thrust vectoring control authority. Each engine has 20 small thrust chambers and is divided into two banks of 10 thrust chambers each. The control of the output thrust level is achieved by varying the chamber pressure (Pc) of each bank, thus providing thrust vectoring.

Fig. 1. X-33 Vehicle

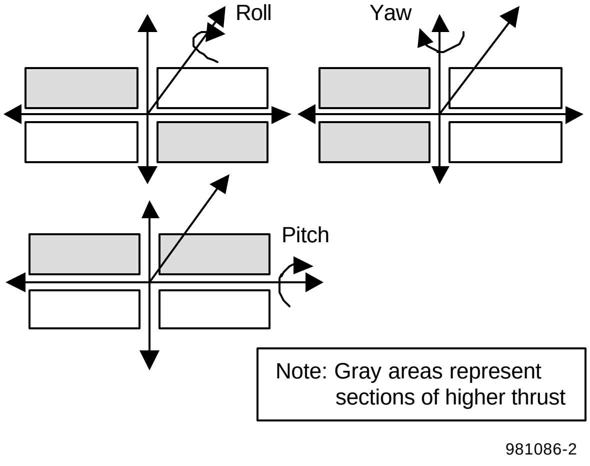

Fig. 2. TVC Diagrams

The input commands to the engine are sent from the vehicle controller in the form of percent Pc and mixture ratio (MR), ratio of oxygen to hydrogen, for each of the four banks (see Fig. 2). 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 Fy forces) is between the diagonally opposite banks. During nominal operating conditions, the two engines have independent control systems. There are two “inter-connect” valves that tie in the two engines under “Power Pack out (PPO) condition, where one of the two Power Packs is shut down. Thus, the yaw control under nominal operation is implemented by throttling each engine individually for differential thrust[3,4].

he actuation system is composed of electromechanical actuators with high response rates and with valves that

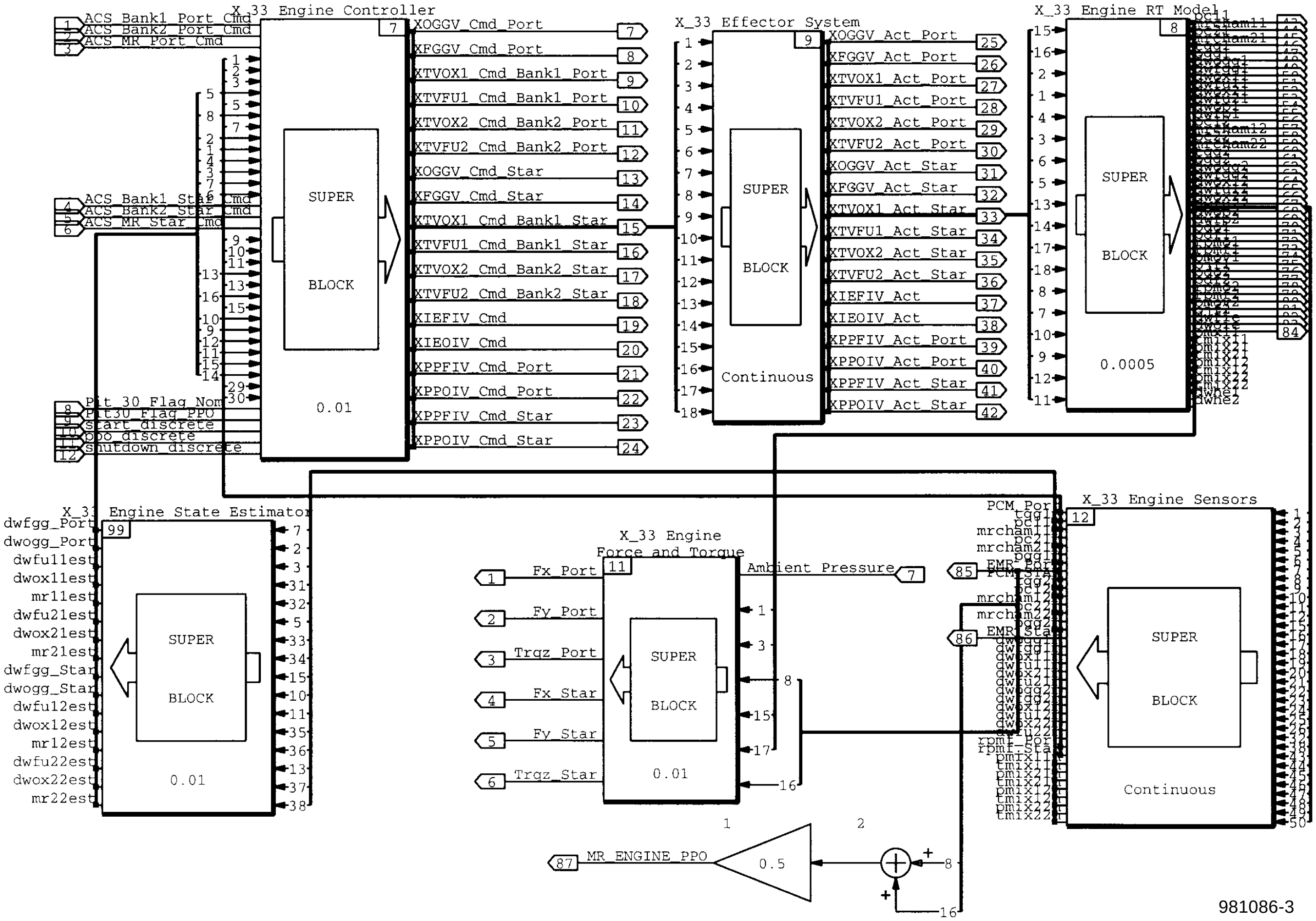

Fig. 3. X-33 Control System Model Matrixx Block Diagram

have inherent dead band and hysteresis modeled into the dynamic equations representing their performance characteristics within the system simulation.

The control system model consists of five parts: (1) controller, including the control laws and implementation logic with all the table look-ups; (2) RTEM representing the engine dynamics with all the nonlinear effects; (3) actuation system model, representing the actuator and valve dynamics with performance characteristics; (4) sensors, representing the sensor delay dynamics; (5) forces and torque table look-up that transform the generated Pc level per bank into x, y, and z directional forces and torque and (6) the state estimator that estimates the MR of each engine from available measurements. Figure 3 shows the Matrix Block-Diagram.

2. ROCKET ENGINE CONTROL SYSTEMS BACKGROUND

The development of control systems for rocket engine propulsion depends, among others, on being able to accurately predict the performance of the engine, the controls, and the engine cycle (e.g. staged combustion, GG, or expander cycle). Computer simulations provide an effective means of analyzing behavior and interaction of these complex systems before full-scale development and testing. Simulations can also serve as aids in solving problems that may arise during and after the development phase. Control requirements are usually driven by the desired performance and deal with limitations in sensors, actuators, valves, controller software, and electronic control devices. The control system is based on overall guidelines to meet the engine performance requirements over the entire operational range plus a margin while maintaining adequate stability and response characteristics.

2.1 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 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. 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.

2.2 X-33 Control System Overview

The control system in the X-33 is much more complex than that of the SSME (Fig. 4). 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, MR control, TVC, and gas generator (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.

1. Thrust Level Control. The overall operating level of each engine is directly related to the GG system power level. This is closed-loop controlled via the GGOV. 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 oxidizer TVC valves.

2. MR Control. Calculated MR is 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.

3. TVC. The X-33 performs thrust vector control by varying the thrust in each of the four banks of the two engine systems. Thus, by generating differential thrust between the upper two and lower two banks, a pitching moment is induced on the vehicle. Yaw control is

achieved via differential thrust between the left and the right banks of the engines. While, roll is derived by adjusting the diagonally opposite banks to a given differential thrust level. The maximum TVC level achievable at any instant under nominal operation is 15% total. 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 for the vehicle. It will still be capable of performing 15% TVC and even 30% pitch maneuvers at PPO.

4. GG Control System: The GG system chamber pressure is controlled via the GG oxygen valve based on closed-loop output feedback from the GG pressure sensor. While 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.

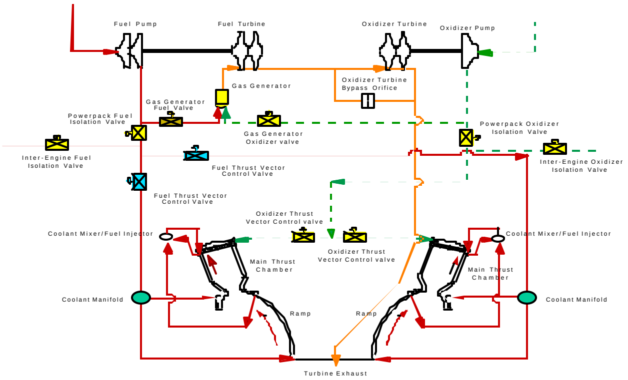

Figure 4. Aerospike Engine Schematic

2.3 X-33 Engine Dynamics

The analytical description of the X-33 engine system is quite involved. The actual RTEM used in the simulations is a lumped parameter representation of all the flow, pressure, speed, and temperature dynamics. It only requires inputs from the controller in the form of valve positions. The two GG valves and the four TVC valves are the main control valves for all operating conditions. The PPOIV and the PPFIV are only required for the start, shutdown and PPO conditions. Finally, the IEFIV and the IEOIV are required for PPO operation to allow propellants to flow to all TC in all four banks.

High temperature fuel-rich gas is produced by the gas generator (GG), that is used to drive the fuel and oxidizer turbines. These are arranged in series and drive the fuel and oxidizer pumps. The propellants for the gas generator come from the main fuel and oxidizer flows and the gases produced are vented to the atmosphere. Two such engines will power the X-33. Each engine has an upper and lower bank of 10 thrust chambers. Thrust vectoring used for Roll, pitch, and yaw maneuvers is done by setting the upper and lower banks of the engines at different power levels. Each engine is to be computer controlled. The fuel turbine inlet pressure, the combustion chamber pressures is closed-loop controlled, and the computed engine mixture ratio is used for closed-loop feedback. The GG temperature is closed-loop controlled only in PPO. During PPO the surviving engine provides propellant to both engines. Inter-engine propellant valves open and allow propellants to flow from the surviving engine to the shut down powerpack. Currently, the start sequence is open-loop and transitions to closed-loop at 5.32 seconds for ground testing and 5.0 for flight. The PPO transition sequence is open-loop and requires one second for completion.

2.4 X-33 Controller

The X-33 controller is a proportional plus integral feedback system that uses a linear output feedback controller to regulate a highly nonlinear engine system. The dynamic equations of the control system can be represented analytically as follows. If it is assumed that the state vector is $\vec{x}(t)$ and the measurement vector is $y(t)$:

$$\vec{x}(t) = \vec{f}(x,t) + \sum_{i=1}^{m} k_i u_i \tag{15}$$

In eq. (15) f represents the vector of nonlinear functions of the engine dynamics and $k_i u_i$ are the feedback controllers for each i. Here the gains k_i are scheduled for the proportional or calculated on-line in real-time for the integral parts of the gains for the GG and TVC oxygen valves. These are functions of MR, Pc or TVC conditions.

$$\vec{y}(t) = H(x,t) \tag{16}$$

In eq. (16), $y(t)$ is the measurement output of the nonlinear engine system and $H(x,t)$ is the time dependent matrix of outputs[5].

The compensator consists of a lag (proportional plus integral) controller with measured and calculated feedback. To evaluate system performance, simulations were carried out using the Matrixx (of Integrated Systems, Inc) System Build software. Block diagrams were built to represent the system analytically. These include: (1) a superblock of vehicle commands emulating the vehicle command system; (2) a controller superblock, representing the compensation network of the gas generator, MR and the bank pressure systems; (3) the effectors superblock; (4) the Real-Time Engine Model, representing the engine nonlinear dynamics, (5) the sensor dynamics superblock;(6) the state estimator block that, based on pressure and temperature sensor data, analytically calculates the flow rates of the fuel and the oxygen to compute the MR achieved and (7) the force and torque superblock, housing the transformation table look-up. The latter transforms output chamber pressure to forces and torques on the vehicle (see Figure 3 for details).

The engine controller comprises seven different modes: (1) Mode 1 is the engine start phase, where the control valves are sequentially opened to throttle the engine power up to main stage via open-loop commands. (2) At 5.32 sec from start, the closed-loop control system takes over and receives and implements vehicle commands in the form of MR and nominal %Pc to carry out thrust vectoring, which is Mode 2. (3) In Mode 3, the engine GG will power up (while TVC activities continue) to accommodate 30% pitch commands. This is required under some predetermined conditions whereby vehicle stability requires larger pitch capability. (4) Mode 4, called PPO, is an emergency mode of shutting down one of the two power packs. During this phase, the power pack system of one engine is cut off while continuing formerly held TVC activities, only proportionally adjusting their levels. Again, open-loop commands will take the GG and TVC valves to their proper positions during the so-called PPO period of 1-sec duration. (5) During Mode 5, the PPO is completed and the closed-loop PPO control starts. Therein, PPO TVC commands are implemented. (6) Again, under some conditions, when 30% pitch is required, Mode 6 is implemented by powering the GG level up in a closed-loop manner while still carrying out TVC commands. Then 30% pitch commands can be performed. (7) The last phase is engine shutdown, Mode 7. Here, the GG and TVC are sequentially closed in an open-loop setting according to predetermined sequencing profiles.

The control system gain schedules are one-dimensional tables or are calculated on-line in a real-time manner for the TVC and GG oxygen Valves.

The complication of the control system logic is even more aggravated by the higher gains necessary during the TVC conditions of operation. Furthermore, the banks that are throttled up require higher gains than those throttling down. Thus, each bank is constantly checked for PL change and special logic determines the occurrence of TVC operation to accordingly, calculate the required gains.

2.5 Frequency Response Analyses

TVC can be carried out by varying the Pc commands of each of the four banks by as little as 0.1% and as high as 15% for vehicle attitude control and ascent trajectories. The GG yaw TVC condition is achieved by throttling each engine powerpack individually up or down to get differential thrust between the left two and the right two banks. The pitch and roll TVC are accomplished by utilizing the TVC valves while the power packs are kept at constant amplitudes.

Thorough nonlinear frequency response analyses were carried out on the model by various sinusoidal inputs to the controller at different power levels(at different frequencies and with different amplitudes) to study the response characteristics (phase and gain) between 0 and 10 Hz at amplitudes between 1% and 15% thrust level. Typical results are shown in Figures 5a, 5b, 6a, 6b, 7a & 7b. The plots in Figures 5a, 6b & 7a represent the phase and 5b, 6a & 7b represent the gain profiles under 98% and 70% power levels. The three overlayed curves represent the model predictions by the Detailed Transient Model (DTM), The Real-Time Model (HSL) and the actual test data carried out during hot fire tests. The HSL and the test match very closely. However, the target performance that is being worked towards is that of the DTM. Currently ongoing enhancement in the controller will get the performance much closer to the DTM. Moreover, the performance at the nominal 80% power level is very close to the target. The plots labeled as TVC indicate a test condition whereby the two banks of the engine are held at 15% TVC (30% apart) and a sine wave command of 2% amplitude and frequencies ranging from 0.3 Hz to 5 Hz are applied. While the GG Yaw maneuvers throttle both banks up by 2% or in the opposite direction by 2%.

As can be seen the frequency response is quite good. The gain at 98% is about 1.7 db and the phase lag is less than 25 degrees for the TVC condition. For Yaw control, the GG system will have to throttle power up or down, thus raising the power level of both banks of the given engine. The performance for yaw is comparable, as seen in the Figures. Herein the gain ranges between 1.8 db to a little over 0.7 dB and the phase is less than 40 degrees. The engine response above a few Hz frequencies is not expected to be significant. Thus, the performance below 1 Hz is important. On the other hand, at 70% PL GG Yaw performance is about 1 dB at 1 Hz for the gain and about 29 degrees in phase. The highest gain below 1 Hz is about 1.7 db at a frequency of 0.7 Hz. Analyses indicate that at low TVC amplitude the phase and gain characteristics are worse than at higher amplitudes. The system nonlinearities, especially those of the effectors place heavy constraints on the control system performance at the very low amplitudes. The optimal performance requirements are currently under evaluation by NASA, LMSW and Rocketdyne, based on detailed six degrees of freedom (6dof) vehicle flight simulations. The engine frequency response performance is satisfactory, according to 6dof simulation results of the target trajectories, and with the enhancements that are being carried out on the controller it is expected to meet the final performance requirements by a very safe margin.

2.6 Effectors

The actuator model is a complete nonlinear model with hysteresis and dead-band developed by Allied Signal in the Matrixx format and anchored to the control system model. Saturation limit on the GG valves is 222 %/sec. Control system ramp rate are always much lower than the limit. The dynamics include coulomb friction and backlash that reflect the valve design characteristics and the electromechanical actuation system behavior. The actuator dead bands are also included as 0.225 degrees for the TVC and 0.416 degrees for the GG.

2.7 Sensors

Pressure and temperature sensor outputs are used in the closed-loop feedback control system. The sensor dynamics are represented by first-order delay equations that reflect their time constants and simplified performance characteristics.

3.0 CONCLUSIONS

The Aerospike is the first rocket engine of its kind with a control system that has a very complex thrust vector control capability with minimal moving parts and relatively high thrust-to-weight ratio.

The Aerospike engine control system performs adequately for attitude and thrust-vector control of the vehicle as based on the 6dof simulations. Complete 6dof simulations with the vehicle model will determine the extent of effectiveness of the controller and will set the target frequency response requirements. Preliminary indications of 6-dof simulations are that the differential throttling is successfully achieved in all directions. Vehicle yaw control has a slower response than TVC pitch and roll control, especially at low PL and low TVC amplitudes.

This revolutionary engine has gone through 6 successful closed-loop control hot fire test. The performance of the control system has been excellent. Satisfactory MR control has been difficult to achieve due to the large delays and non-repeatability in the temperature sensors. These were used for the TVC fuel valve control system. However, currently the TVC valve positions and PC are being used to calculate fuel flow and thus control MR. This approach is working well.

4.0 REFERRENCES

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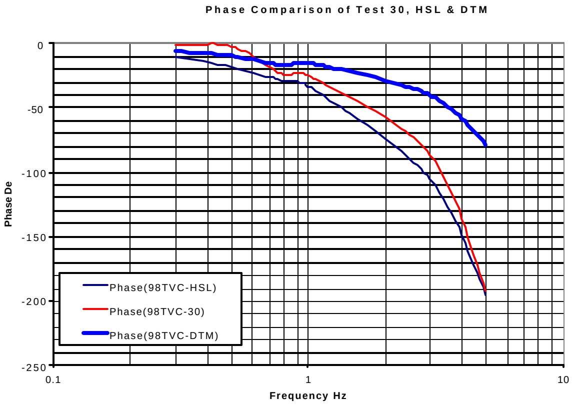

Figure 5a. TVC Pitch Maneuver Phase Plot At 98% PL, AMPL=2%

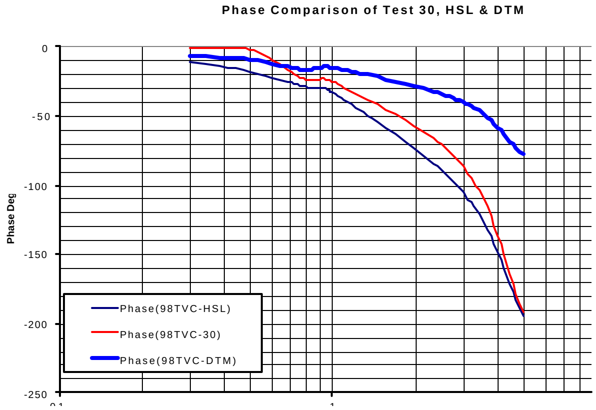

Figure 5b. TVC Pitch Gain Plot At 98% PL, AMP=2%

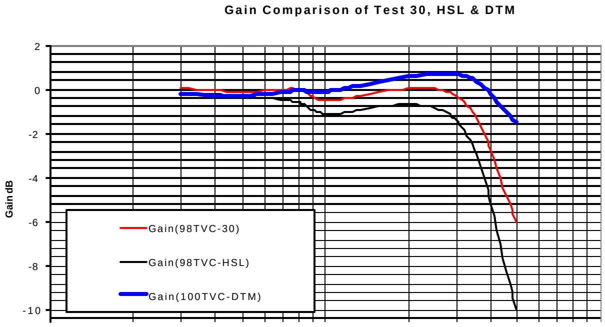

Figure 6a. GG Yaw Gain Plot At 98% PL, AMPL=2%

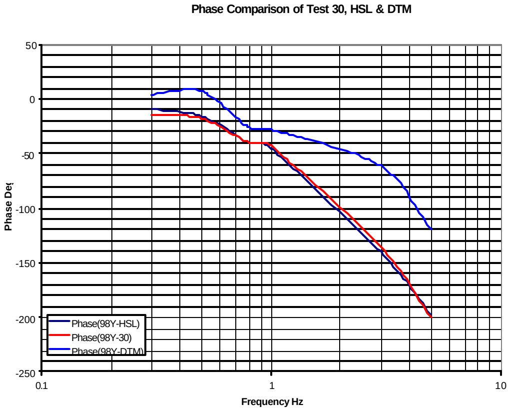

Figure 6b. GG Yaw Phase Plot @98%, Amp=2%

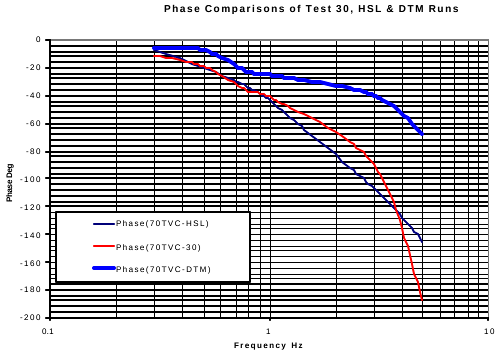

Figure 7a. TVC Phase Plot @70%, Amp=2@

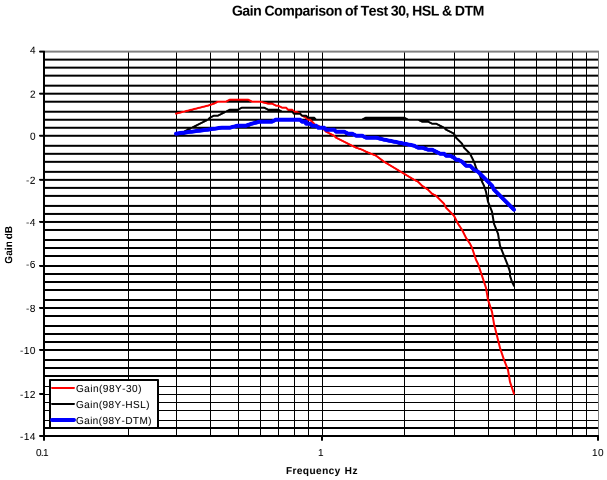

Figure 7b. TVC Gain Plot @70%, Amp=2%