Development of a Flight Propellant Regulation System for Hall Effect Thrusters

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In 1996, NASA Glenn Research Center funded the development of a Multi-Function Valve (MFV) at Marotta Scientific Controls, Inc.[1,2,13,14,15] The MFV was developed to provide the modulating regulation of a mechanical regulator with the positive closure and variable set-point capability of an electronic regulator, specifically for use in Electric Propulsion systems using xenon, argon, or krypton as propellant. During this Small Business Innovative Research (SBIR) program, which was completed through Phase II, an Engineering Model (EM) valve was developed. This valve underwent significant operational and environmental testing, as well as several integrated test programs with Hall Effect Thrusters (HETs).[3,4,5] In addition, a detailed control theory model was developed to optimize operational fluid mechanical parameters and the electronics controls topology. This paper presents the work being performed by Pratt and Whitney Chemical Systems Division and Marotta Scientific Controls, Inc. to complete the flight development of the MFV. The MFV Propellant Regulation System (PRS) includes components in the Power Processing Unit (PPU), the MFV, and the hardware of the Propellant Management System (PMS), of which the MFV is a sub-component. Discussed are details of the Phase II SBIR numerical control theory model and the transition of this model to a functional design tool to optimize system

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performance. Also discussed is the development status and qualification planning to develop this product. This MFV based PRS is being developed for use with Pratt and Whitney's Hall Effect Thruster systems, as well a component for use by other satellite manufacturers.

Introduction & Background

Pratt and Whitney CSD is developing HET propulsion systems for use on commercial and military spacecraft. These systems are composed of several subsystems, including the PMS. The flight PMS under development by CSD includes the Marotta MFV as the PRS component.

In August of 2001, Pratt and Whitney CSD and Marotta signed a Teaming Agreement to pursue the development of a flight PRS based on the MFV. Marotta has provided Pratt and Whitney in-depth technical information regarding the MFV's operational characteristics, and access to control theory software previously developed by Marotta under contract to NASA GRC. Based on this input, Pratt and Whitney CSD, in conjunction with Marotta Scientific Controls, have developed a control theory model that can be used to define the fluid dynamic control laws for any thruster configuration employing a xenon (or other gas) PMS. In addition, Pratt and Whitney CSD is developing the flight electronics required to operate the MFV for its flight PPUs. Pratt and Whitney CSD is also offering the MFV and electronics for sale for use in other HET systems with access to the controls software as an integration tool.

The Magnetostrictively Actuated Multi-Function Xenon Gas Valve (MFV) was developed as part of the work performed under two Ballistic Missile Defense Organization (BMDO), SBIR contracts. The design validation and performance testing was performed in two phases plus extended testing. Phase 1 was comprised of stand-alone MFV performance testing that included end-of-life cycle and leakage tests. Phase 2 was comprised of in-system tests and included pressure transducers as well as anode current feedback control with a T-160 at NASA-LeRC, similar testing at with a T-140 at TRW, high pressure (>3,000 psig) Xenon operation, and random vibration. The MFV has undergone further testing with a RITA Thruster at Giessen University.[5]

In addition the MFV has been evaluated by NASA as part of an effort to investigate proportional control valves for potential use in electric propulsion feedsystems.[7]

The main design goal of the MFV was the simplification of typical xenon PMSs by incorporating propellant regulation and flow control into a single component. Flow regulation through the MFV is achieved by applying current to a standard valve solenoid. This current flow causes a deformation in the magnetostrictive material of the MFV, which in turn displaces the valve's poppet, providing control of the flow of propellant.

Use of magnetostrictive material in the MFV and the associated poppet design result in a proportional flow control design with significant gain advantages over competitive spring and poppet technologies. These gain differences are significant enough to allow the MFV to regulate the propellant flow over a broad range of inlet pressures without any regulation instabilities. Stable propellant flow regulation can be achieved with an MFV based PRS without the additional requirement of a pressure regulator.

PMS Topologies

In concert with Pratt and Whitney's Hall Effect Thruster system development effort, flight configurations for a variety of xenon PMSs have been evaluated. Typical variations to these systems include required number of isolation valves and redundancy requirements.

Historically, xenon propellant fed systems used two main stages, a pressure regulation section to account for the drop in tank pressure over the life of the application, and PRS. A typical flight pressure regulation system is comprised of a single or dual stage pressure regulator, or a bang-bang accumulator device.[8,9] Flight PRSs typically use a thermal throttle or temperature compensated orifice to set the propellant flow rates.

The Pratt and Whitney CSD PMS is based upon the Marotta MFV for both the pressure regulation and PRS functions. Pratt and Whitney CSD is currently developing flight control electronics for use with its PPU to operate the MFV.

Propellant Regulation System

Flight PRS with MFV

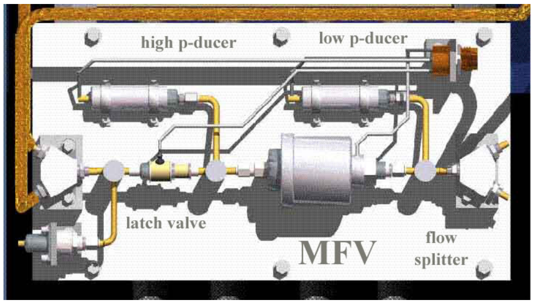

Figure 1 – Typical MFV Based Flight PMS

Figure 1 shows a single-string PMS plate utilizing the MFV. Propellant is provided to the plate from propellant tanks on the left. An additional latch valve is shown for isolation redundancy. On the right, downstream of the MFV, is an orifice block 'flow splitter' to provide the correct amount of propellant flow to the anode and cathode of an HET.

Also shown are pressure transducers upstream and downstream of the MFV. The downstream transducer is required for thruster ignition, the upstream transducer shown in Figure 3 was intended to monitor tank pressure during loading.

MFV design

The construction of the MFV (Figure 2) is similar to that of a normally closed, pull-type plunger solenoid valve. In the MFV design the plunger (or armature) is replaced by magnetostrictive material, TERFENOL-D. As the current flowing in the solenoid coil creates a magnetic field, the magnetostrictive material grows in length, eventually contacting the poppet that seals against the valve seat. The poppet lifts away from the seat as magnetostrictive growth continues from increased magnetic field. Valve modulation is achieved by controlling the stroke, which is a function of the magnetic field and thus coil current.

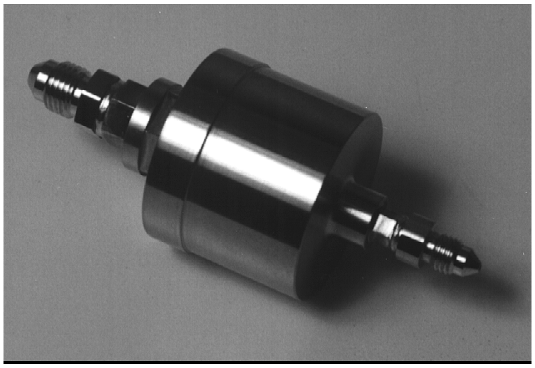

Figure 2 – Multi-Function Valve

TERFENOL-D is solid state crystal comprised of Terbium, Iron and Dysprosium.[10] The TERFENOL-D component used in the MFV is pre-stressed to improve the strain output response. This pre-stressing mechanically forces the internal magnetic domains of the material to align along the crystal structure of the material. TERFENOL-D is used in sonic tranducer applications operating at 12-13 kHz, and therefore has demonstrated unlimited cycle life for the MFV application.

Mechanically, the valve poppet and the magnetostrictive material are preloaded independently by their respective springs. Motion of the magnetostrictive material controls the motion of the poppet after a fixed pretravel has been achieved. The increased stress imparted to the magnetostrictive material lifts the poppet. The valve is closed when the magnetic field is removed causing the magnetostrictive material to revert back to its initial dimensions.

The inherent high force of the magnetostrictive material, from strain, permits larger sealing loads than a standard spring and poppet valve configuration. The metal-to-metal sealing in the MFV results in internal leakage values of less than 1x10^{-5} sccs GHe.

MFV Operational Characteristics

Closed loop PRS operation

Operation of the valve is always performed using 'closed loop operation', utilizing either pressure or thruster discharge current data to control the set point. Figure 3 outlines the operating characteristics of the valve the start transient of a typical HET; prior to discharge initiation a pressure transducer downstream of the MFV regulates propellant flow to the thruster. The control loop using this pressure data allows for optimization of thruster ullage pressurization.

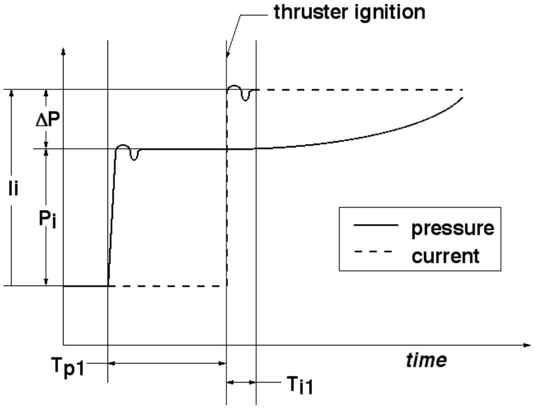

Figure 3 – HET start transient

After the thruster discharge is initiated, the discharge current from the thruster is used as the control parameter to regulate propellant flow. For a typical P&W CSD HET, thruster discharge current is proportional to propellant mass flow rate.

In Figure 3, P_i is the unaugmented thruster pressure, T_{p1} is the time to pressurize the thruster and plumbing ullage, I_i is the initial discharge current set-point of the HET, T_{i1} is the time delta between thruster discharge ignition and switching the control loop from pressure to discharge current control, and ΔP represents the pressure increase in the thruster due to thermal effects.

Open loop thruster Operation

Preliminary testing performed with the valve in 'open-loop' operation for HET start-up was performed to determine the viability of operating the valve without a control loop. In a flight application, operation of the valve in open loop operation at a constant current set point was considered impractical. The stoke required to establish propellant flow with a proportional flow valve varies with tank pressure; if there is no regulator upstream of the valve, a single set point would result in a broad range of start-up propellant flows over the life of the flight system. In addition, using a fixed set point might have required excessively tight manufacturing controls to maintain repeatability.

Another open loop method was evaluated by pulsing the ullage to establish enough propellant flow to ignite the discharge of the HET prior to ignition. Even though successful thruster operation was achieved in test, this method was also determined to be difficult to operate feasibly with a flight system.[3,12]

Numerical Simulation

Historical

In the early part of 1998 a computer model of the Multi Function Valve was developed using a modeling tool called Advanced Continuous Simulation Language (ACSL) manufactured by MGA Software in Concord, MA. The computer model was developed as part of SBIR program and included all of the multi-systemic state equations and interactions including the magnetostrictive and magnetic behavior, the electronics system with the associated control logic, the mechanical system of the valve internals, system ullage and the pressure system in which the valve operates. This ACSL based model has been successfully migrated to a MATLAB based modeling and simulation tool in the early part of this year as part of the PRS development program.

This model is available to all potential customers to simulate the dynamic response of HET or Ion thruster systems. This tool is helpful in determining the control bounds and impacts of various plumbing geometries, tank blowdown impacts, and differing levels of propellant flow rates for different thruster applications.

Model Capabilities

The MFV model provides a parametric design tool to rapidly optimize the control electronics to meet varying system requirements for both a pressure control and anode current control system. The model has a proven ability to predict the mechanical and electrical subsystems very accurately, however, more work is required to verify model accuracy for a given system configuration. The model has been constructed utilizing detailed valve parameters including a mathematical model of the magnetic circuit, valve coil, magnetostrictive material and valve mechanical configurations, dynamic behavioral model of the valve poppet including all reaction forces acting on the poppet. Also included is a complete model of a typical pressure system with the various ullage volumes, and the pressure and anode current closed loop servo control system.

Model Description

The Matlab/Simulink model was constructed to operate in continuous time mode, but can be altered to operate in discrete time mode. The model is somewhat complex and includes many nonlinear components, which present a problem in performing frequency response analyses using Matlab's tools that are designed to modify a nonlinear system to one that is linear time invariant. These linearizing tools work well enough on simple systems, but accuracy decreases rapidly with increased complexity and nonlinearity. Other methods, thus, were employed for generating frequency response data.

The system contains both fast and slow dynamics (i.e., a stiff system), the MFV having a small time constant with respect to the time constant associated with the plumbing. In order for the simulation to run efficiently, proper choice of a solver was essential. Matlab offers several solvers suitable for stiff systems; the ODE 15s (stiff/NDF) proved to be most effective for this system.

Figure 4 - Top Level of the Model's Hierarchy

The topmost level of the model hierarchy, shown in Figure 4, separates the model into the Satellite PPU and the Xenon Feed System. Ullage pressure and mdot, which is the anode mass flow rate represented by the anode discharge current, provide feedback from the Xenon Feed System to the Satellite PPU. The current feedback to the Satellite PPU shown in the figure is the MFV drive current.

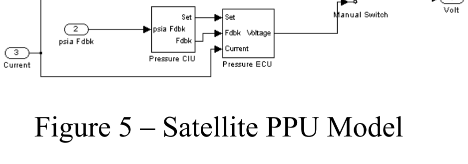

Figure 5 – Satellite PPU Model

The Satellite PPU module, shown in Figure 5, indicates an early stage of the model in which independent pressure and mass flow feedback loops were employed, where a manual switch was inserted into the model to allow toggling between the two loops. As described in the analysis section below, the loops were altered to an inner pressure loop and an outer mass flow loop configuration.

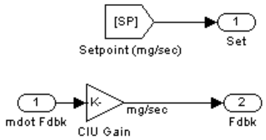

Figure 6 - Flow Command Interface Unit (CIU)

The Flow Command Interface Unit (CIU), indicated in Figure 6, is utilized to provide the command input and to convert the feedback, which is in units of volts, to mg/sec for comparison with the command input.

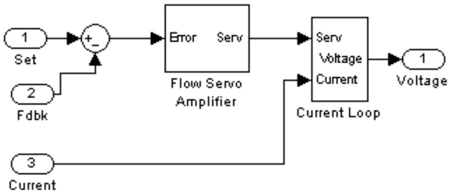

Figure 7 -Flow Electronic Control Unit (ECU)

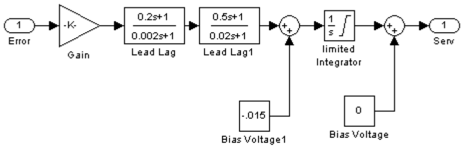

Figure 8 – Flow Servo Amplifier

The Flow Electronic Control Unit (ECU), Figure 7, is comprised of the summing junction for the flow command and flow feedback, a servo amplifier, and a current loop module. The Flow Servo Amplifier, shown in Figure 8, amplifies the command/feedback error and provides compensation through the two lead lag blocks and the integrator. Bias voltage blocks are added to the signals to allow the effects of various offset voltages to be investigated.

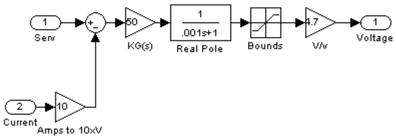

Figure 9 – Current Loop Module

The current loop module, Figure 9, simulates a current source for driving the valve. The MFV current is converted from the units of amps to volts for comparison with the output voltage from the Flow Servo Amplifier. The voltage difference is then amplified, compensated, followed by power amplification for providing a suitable voltage (and adequate current capability) to the MFV.

Figure 10 – Xenon Feed System

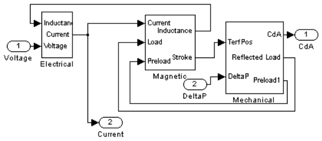

Figure 11 - Multifunction Valve

The Xenon Feed System, shown in Figure 10, consists of the MFV and the plumbing. The MFV module provides the effective valve area (CdA) as input to the plumbing block, which in turn feeds back to the MFV block the pressure across the valve. Figure 11 shows how the electrical, magnetic, and mechanical subsystems of the MFV module are interrelated. Current calculated in the electrical block is fed to the magnetic block, which utilizes the current and mechanical loads to determine the electrical inductance and mechanical stroke of the magnetostrictive material. The stroke is fed into the mechanical subsystem to determine the CdA input to the plumbing.

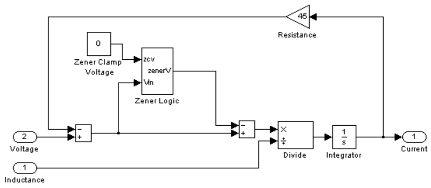

Figure 12 – MFV/Electrical

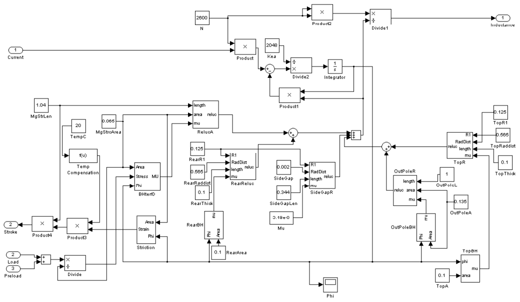

Figure 13 – MFV/Magnetic

The MFV/Electrical block, indicated in Figure 12, calculates the current for a voltage across a coil with resistance (i.e., $V_{coil} = IR + Ldi/dt$). The MFV/Magnetic subsystem, shown in Figure 13, calculates the reluctance of the magnetic circuit based on the total valve geometry, which is dependent upon the load, and this reluctance value in turn is used to calculate electrical reluctance ($L = N^2/\Re$) and flux ($d\phi/dt = (NI-\Re\phi)/K$) in the valve's magnetostrictive material.

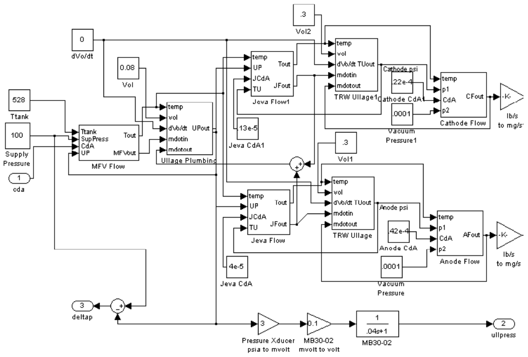

Figure 14 - Plumbing

Figure 14 illustrates the layout of the plumbing subsystem. Included in the plumbing system are the supply pressure tank, ullage components and flow restricting orifices. Temperature variations and sonic/subsonic flow conditions are accounted for in pressure drop and flow rate calculations. This subsystem is where modifications can be readily implemented to evaluate various system geometries, perform trade studies, and determine system stability.

Figure 15 shows the output for a test case with a 0.6 psia ullage pressure command, which resulted in a total anode/cathode flow rate of 1mg/sec. Typical flight volumes and flow restrictions were used for this analysis; stable flow was achieved within three seconds.

Analysis Results

The control model discussed above was used to analyze the system and determine how it could best be controlled.

Open Loop Frequency Response

The open loop frequency response is used here as an analysis tool to determine the optimum system closed loop compensation. This analysis is critical for designing a control algorithm. Once the small signal open loop response is available, a linear control system can be designed to meet the system response requirements. Based on initial analysis of the closed loop system, the best control approach was to sense the mass flow through the anode current feedback, and generate an error based on this feedback. This error would then be compensated and used as a pressure command. The pressure command will be used as an inner loop for an ullage pressure control circuit.

Another system characteristic that was revealed by the closed loop analysis is that the pressure response is highly dependent on the tank pressure. This is intuitively obvious in that the rise in pressure downstream of the valve will depend on the pressure upstream.

It was therefore obvious that what was needed was a robust control algorithm that could control the ullage pressure over a wide range of tank pressures.

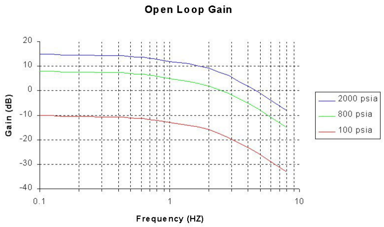

Figure 16 – Open Loop Gain

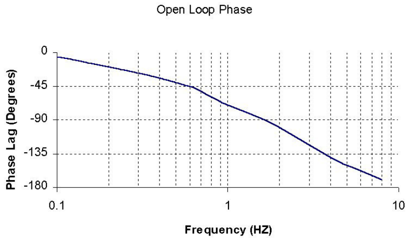

Figure 17 – Open Loop Phase

Accordingly, the model was used to calculate the open loop pressure response as it varied with the tank pressure. The command was set at the input to the valve current control circuit. The output was the ullage pressure, as measured by the electronics (measured in volts). The results of this are shown in Figure 16 (gain) and Figure 17 (phase). These figures show that the tank pressure does not effect the phase, but the gain is effected quite dramatically. There is a 25 dB difference between the gain with a tank pressure of 100 psia compared to the system with a tank pressure of 2000 psia.

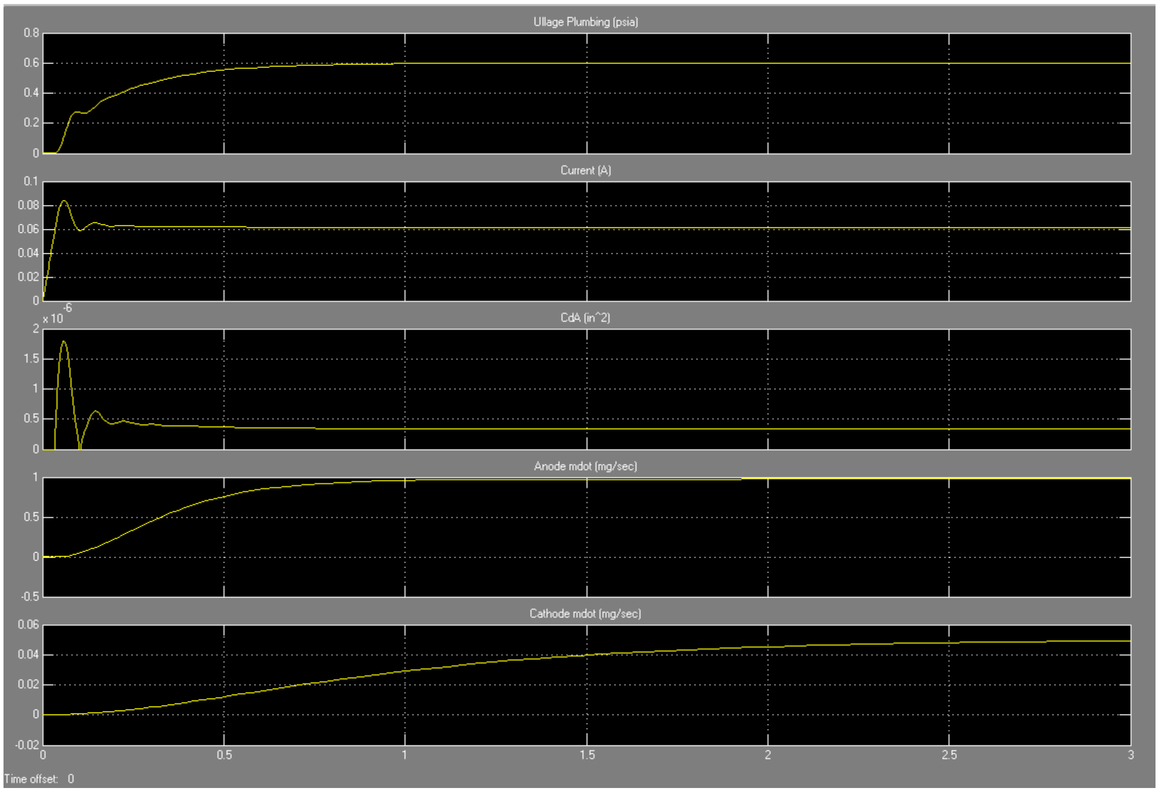

Figure 15 – Control Model Output

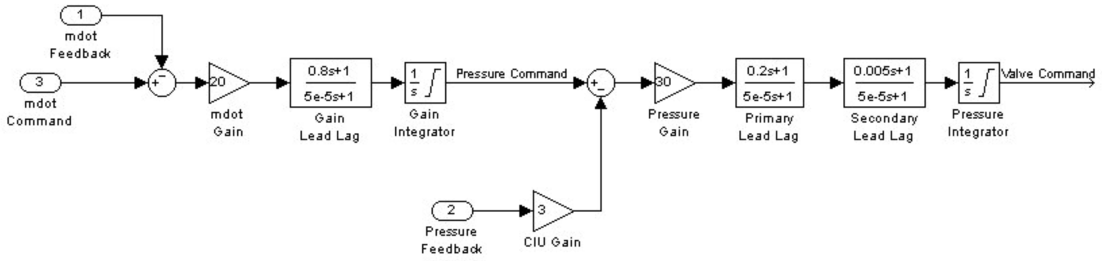

Figure 19 – Control Block Diagram

Analysis Method

With the open loop frequency response established, a control circuit was designed to provide a second order response over a range of pressures. It was obvious from the flatness of the response at low frequency that an integrator was needed. Adding a lead-lag term would then improve the phase margin and therefore stability.

This basic approach was tested by adding the linear algorithm to the block diagram and simulating the ullage pressure response over a range of tank pressures. While stable over the range of pressures, the system did show some oscillation at the higher pressures. Accordingly a secondary lead term was added to provide additional phase margin.

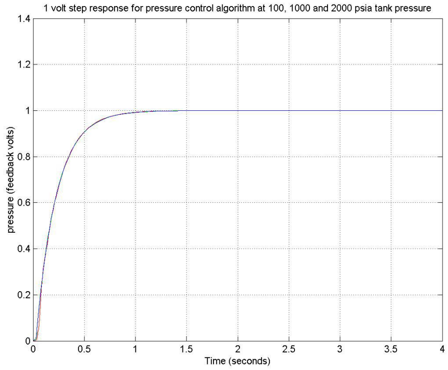

Figure 18 – Ullage Pressure Step Response

The result of this was a system response that was almost immune to tank pressure changes. Figure 18 shows the step response for an ullage pressure command. The response is almost identical regardless of tank pressure. The amplitude of this step command was sized to 1 volt of command, since that is a convenient level for the math model.

Outer Current Loop

The desired end result of the control algorithm is to control the discharge current and therefore the mass flow. After closing the loop around the pressure, it was relatively simple to design an discharge current control algorithm. An integrator was obviously needed to eliminate steady state error. A lead-lag circuit was added to improve the phase lost by the integrator. The block diagram for the entire pressure and mass flow control algorithm is shown in Figure 19.

The result of the control algorithm shown in Figure 19 matches the system we desired from the start. It is a robust algorithm that delivers consistent stable control over the full range of tank pressures. It has essentially no steady state error thanks to the integrator circuit. It is also extremely responsive, delivering 90% of the commanded pressure within less than a second in all cases. Figure 20 shows a step response to an mdot command. The system is extremely responsive over the range of pressures. Again, the step amplitude was taken as 1 command volt for convenience in running the model.

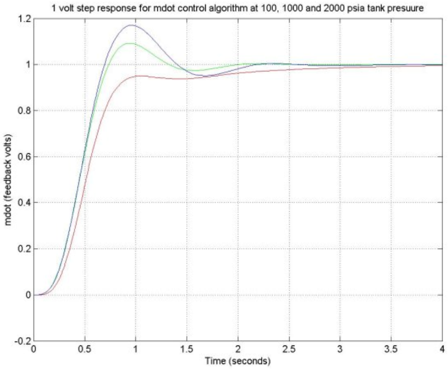

Figure 20 – mdot Step Response

Valve Gain Sensitivity

Analyses were performed to evaluate the effect of valve 'gain' on the ability to regulate propellant flow rate over a range of inlet pressures, and to determine the effect of these gain differences in the control process. Gain was taken to be the valve's overall response to input current, as measured in sccm/amp. Comparisons were preformed for valves with gains of 300,000 sccm/A and 20,000 sccm/A.[4,11,12]

It was found that the 300,000 sccm/A valve resulted in a larger change in the gain as the tank pressure changed. For the 20,000 sccm/A valve the open loop gain changed by about 25 dB as the pressure varied, for the 300,000 sccm/A this dynamic change was over 40 dB. In addition, the 300,000 sccm/A valve had lower resolution, making it harder to accurately control the mass flow.

Electrical Design

Analog vs. Digital Trade Off

One key hardware question is whether the control electronics should be analog or digital in nature. Analog electronics are simpler, generally less expensive and don't require software or firmware. Digital electronics, while more expensive are extremely flexible and are able to handle nonlinear control much easier than analog circuits.

Based on the above results, the tentative decision is to proceed with analog electronics. The control does not require any sophisticated adaptive control or other nonlinear algorithms. The basic lead-lag and integrator circuits can easily be constructed with analog circuits. All of these factors tend to drive the design towards analog circuitry.

Analog Circuit

A basic analog control circuit to implement the electronics control design is shown in the block diagram in Figure 21. No attempt has been made to create the exact poles and zeros, since this is still being evaluated.

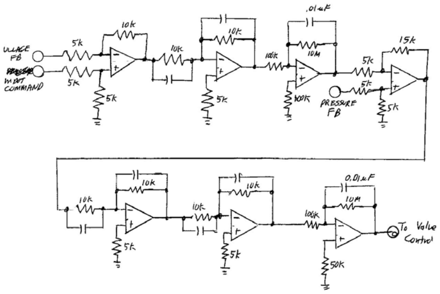

Figure 21 – Control Circuit

MFV Based Test-bed

A PRS test-bed is being developed to allow operation of the MFV with a variety of Hall Effect and Ion thrusters. This test bed is based upon the system developed at TRW in 1998, and will be used to develop Pratt and Whitney's flight electronics design.

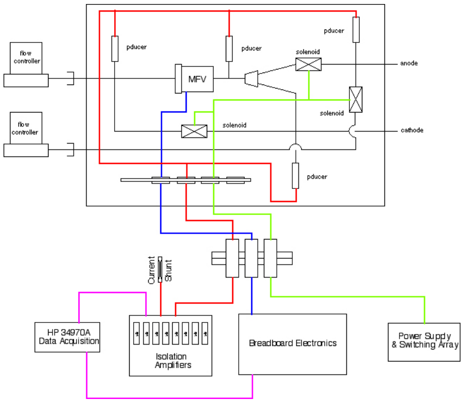

Figure 22 – CSD MFV Laboratory Test-bed

This test bed, shown in Figure 22, is comprised of a valve plate, laboratory propellant flow controllers, and an electrical test system to interface with laboratory or flight PPU's and HETs or Ion thursters.

The valve plate incorporates an MFV, three Marotta solenoid valves, three pressure transducers and a mechanical interface for connecting propellant lines. Downstream of the MFV are a pair of LEE viscojets to provide the required flow split between the anode and cathode legs an HET. This arrangement allow the MFV to be placed inside a vacuum test chamber, and to operate an HET with the MFV or via UNIT 1551 laboratory flow controllers.

The electrical test system interface consists of an I/O section of 5B isolation amplifiers, an HP 34790A multiplexed data logger, a flight electronics controller, and a switching controller for the solenoid valves. Start-up will be in closed loop operation with pressure feedback control; a voltage signal will provide a status indication that the PMS is ready to ignite the thruster. Steady state propellant flow control will be performed closed loop based on thruster discharge current.

The test bed will be used to operate the MFV in concert with P&W CSD's laboratory HETs and PPUs. This test bed will also be used to optimize the flight electronics currently in development. A turbo molecular pump, with additional flow restrictions, will be installed on the anode and cathode legs to operate the test bed without an HET.

This resource is available for all potential customers interested in operating the MFV with an HET or ion thrusters.

Conclusions

Pratt and Whitney Chemical Systems Division, in conjunction with Marotta Scientific Controls, Inc., are completing development of a flight Propellant Management System for use with Pratt and Whitney CSD's line of Hall Effect Thrusters. The key component of this PMS is the Marotta Multi-Function Valve, and the associated electrical circuitry required for operating the valve in a HET based propulsion system.

Use of the MFV, with its magnetostrictive technology, enables a PMS to be used, without a pressure regulator, to provide stable propellant flow to either an HET or Ion thruster over the typical blow-down range of a xenon based satellite propulsion system.

A control simulation model was re-developed based on work performed by Marotta previously under an BMDO Phase II SBIR contract. This model allows for the simulation of various propellant feed system geometries to determine system level requirements to drive the MFV.

In addition, Pratt and Whitney CSD is completing a laboratory PMS test-bed using the MFV as the PRS, in conjunction with laboratory flow controllers. Both the laboratory test bed and the simulation model will be used by Pratt and Whitney CSD to operate and optimize it's HET based propulsion systems, and are available for use by potential customers of the MFV based PMS.

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