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CONTROLLER MODELING AND EVALUATION FOR PCV ELECTRO-MECHANICAL ACTUATOR

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Background

Hydraulic actuators are currently used to operate the propellant control valves (PCV) for the Space Shuttle Main Engine (SSME) and other rocket engines. These actuators are characterized by large power-to-weight ratios, large force capabilities, and rapid accelerations, which favor their use in control valve applications. However, hydraulic systems are also characterized by susceptibly to contamination, which leads to frequent maintenance requirements. The Control Mechanisms Branch (EP34) of the Component Development Division of the Propulsion Laboratory at the Marshall Space Flight Center (MSFC) has been investigating the application of electro-mechanical actuators as replacements for the hydraulic units in PCV's over the last few years. This report deals with some testing and analysis of a PCV electro-mechanical actuator (EMA) designed and fabricated by HR Textron, Inc. This prototype actuator has undergone extensive testing by EP34 personnel since early 1993. At this time, the performance of the HR Textron PCV EMA does not meet requirements for position tracking.

Hardware

Dual 14 hp brushless DC motors are mounted to common valve shaft. Two motors are used to provide redundancy, but only one motor operates at any given time. A single rotary variable differential transformer (RVDT) is used for shaft position sensing, while dual resolvers are used for motor position sensing. A triple pass gear arrangement with an overall ratio of 85:1 couples the motor shaft to the valve. A pneumatic cylinder backup system is also provided to close the valve completely in case of control system failure.

A combined analog/digital electronic controller board is used to operate the brushless DC motors. The HR Textron EMA controller sequences the current flow to the coils through three integrated gate bipolar transistors (IGBT's). A resolver-to-digital interface chip uses the resolver position feedback to determine which IGBT and coil to energize next. The resolver-to-digital chip also provides an analog voltage proportional to the motor velocity, which is used as an additional feedback signal in the controller circuitry. The output signal from the RVDT is used to provide a conventional position control loop as well. The controller board is designed to be a "drop-in" replacement for the current hydraulic PCV actuator controllers. The interface is designed to be transparent to the Honeywell SSME engine controller, i.e., the engine controller is unchanged and operates as if a hydraulic actuator were in place.

Objectives

In the current state, the PCV EMA actuator and controller is not able to meet the desired position tracking performance. To address this problem, the goals and objectives of this summer's project were:

a) develop an analytical model to predict PCV EMA performance,
b) verify the model with experimental results,
c) modify the modeled controller to reduce tracking errors,
d) incorporate controller changes in prototype hardware, and
e) test the modified controller for acceptable performance.

The remainder of this report will focus primarily on the first two items, with some discussion of the last three.

PCV EMA Controller Model

The simplified model (shown below in Figure 1) was developed for the PCV EMA which assumed a conventional permanent magnet DC motor and a lumped inertia due to the motor shaft, gearbox, and valve. This model uses the same controller structure as the prototype hardware, for example the position and velocity feedback's and both voltage and current limits. The final version of the model was developed by adjusting parameter values to fit the experimental results.

Most of the parameter values were developed from a step response of the prototype. The initial slope of the step response gives the maximum acceleration capabilities of the system, which is determined by $\dot{\omega}_{max} = K_t\, i_{a,max}/J = 2600\,\mathrm{rad/sec^2}$. Since $i_{a,max}$ is assumed to be known, the values for K_t and J were adjusted to give the appropriate values. With an ideal DC motor, the torque constant is related to the back EMF constant, so these two values were adjusted together to give the maximum velocity shown in the step response. The motor resistance and inductance were adjusted to give approximately the same "curved" response near the maximum velocity.

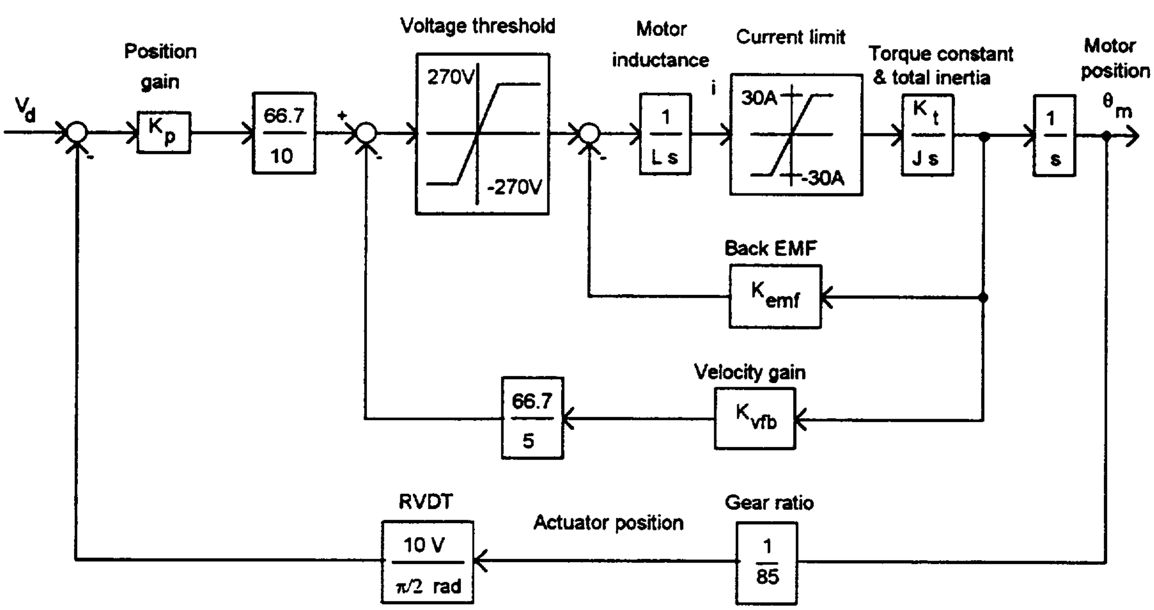

Figure 1 - Simplified Model for PCV EMA

Model Performance and Results

Experimental and simulation results are availiable for the nominal position gain of 5.8 as well as gains of 4.8 and 6.8. Space limitations prevent their display in this report. Note that all testing and simulation of the PCV EMA system was done in the unloaded state. The simulation results closely match the experimental output, particularly while the valve is opening (position increasing). Frequency response tests for both the simulation and experimental hardware were also conducted. The analytical or simulation results were obtained by applying discrete sine wave inputs to the model and continuing until steady-state was reached. The experimental results were obtained from a sine sweep (from a function generator) applied to the hardware. Although the data for the two curves (simulation and experimental) were obtained differently, the general trends appear to match. The close match between the simulation and experimental results indicates that the model is a reasonable representation of the experimental system. The modeled controller can be easily modified for improvements in tracking error which could be tested later on the prototype hardware.

Controller Improvements

From the simplified controller model, the steady-state error for a ramp input is given by the following equation

$$\text{Tracking Error} = \left(\frac{2NK_{vfb}}{K_p K_{RVDT}}\right)(\text{Ramp Magnitude})$$

where K_{RVDT} is the fixed gain of the RVDT position transducer, and the other terms are defined below. Since the gear ratio N is also fixed, the tracking error for a constant ramp magnitude can be reduced by one of three ways: increasing the position gain, K_p, decreasing the velocity gain, K_{vfb}, or add a compensator (integrator, phase lag/lead, etc.).

Step responses of the model with different position loop gains K_p were determined. With a small step of ± 1 degree applied, no overshoot was apparent, even at the large gains of 15 and 20. With a larger step of ± 5 degrees applied, the response associated with a gain of 20 showed a pronounced overshoot, while the remaining gains did not. Finally, the responses to a ± 30 degree step were found. Essentially all of the gains (except the nominal value of 5.8) cause some overshoot. The overshoot responses would be a problem if the PCV were operated near one of the position limits (approximately 0 and 85 degrees). However, the Honeywell SSME engine controller reportedly limits its outputs to 3% of full stroke per 20 millisecond sampling period. This would prevent the system from requesting large step changes in the PCV.

The analytical model indicates that increasing the position control gain to 15-20 is a simple means of improving the PCV EMA controller performance. However, excessive overshoot occurs for large step inputs (which do not occur with the Honeywell engine controller). Unfortunately, attempts to verify the analytical results led to an electrical failure in the prototype controller. Two of the three IGBT power transistors were "blown" during a test with large (+/- 30 degree) step inputs. Several other circuit components associated with the IGBT drivers were also destroyed during the mishap. Since only a single PCV EMA controller circuit board exists, a repair effort was begun.

Controller Debugging

The prototype EMA PCV controller board was difficult to repair due to a variety of reasons including inconsistent documentation, inaccurate circuit diagrams, and uncommon (or not readily available) circuit components. For example, the written documentation which accompanied the PCV EMA hardware was evidently for an earlier version of the controller which had since been changed. The latest set of circuit schematics were in general agreement with the actual hardware, but many significant differences existed. Finally, many of the electronic components on the controller board were not readily available from NASA sources. Some damaged components were replaced with the nearest equivalent part which was available. For example, the original Toshiba #MG100J2YS9 IGBT's were replaced with Powerex #CM100DY-12E models which were of similar, but not identical rating. Instrumentation and technical assistance from EB24 personnel (particularly Justino Montenegro) was invaluable in repairing the damaged controller board.

The efforts to "debug" the PCV EMA controller board were undertaken for two reasons; to repair the system so testing could continue, and to determine the cause of failure. Since the original failure occurred during large (± 30 degree) step inputs, early speculation was that voltage spikes on the power lines caused the IGBT's to fail. However, testing during the first week of August indicated that the existing system maintains voltages of less than 300 volts (with a nominal voltage of 270 volts). Since the IGBT's are rated at 600 volts and the system does not suffer from voltage spikes, it is unlikely that this is the source of the system failure, or that additional "snubber" networks would prevent future failures.

The most likely cause of the system failure was the electrical design and/or the power dissipation capability of the IGBT's themselves. The safe operating area for the Toshiba #MG100J2YS9 IGBT's depends on both collector current (which goes to the motor coils) and the collector-emitter voltage. Although these IGBT's are "rated" at 600 volts and 100 amps, clearly these two values do not apply simultaneously. The operating level for the current PCV EMA controller appears to be marginal for continuous operation over a 0.25 second period. If the power dissipation capabilities of the IGBT did not cause the system failure, then the most likely cause is the physical construction of the prototype circuit board. The overall appearance of the controller gives it an experimental "look" which does not inspire confidence in its performance or longevity.

Conclusions

1) A simple analytical model which treats the brushless DC motor as a conventional permanent magnet DC motor has been developed which matches the prototype PCV EMA performance. A computer program is available for simulating this model's performance with a variety of commanded inputs.
2) The simulations and initial testing results indicate that increasing the position gain to the level of 15-20 should provide acceptable performance for typical ramp type inputs. Excessive overshoot will be a problem at these gain levels if large step inputs (of ± 5 degrees or more) are applied.
3) It is unlikely that additional "snubber" networks placed on the IGBT's of the prototype controller board would prevent system failure if large step inputs were applied.
4) The power dissipation capability of the IGBT is the most likely cause of the system failure. Large step inputs cause an excessively long series of relatively long duration (100-200 μsec) pulses to be applied to the IGBT's. Manufacturer's data indicates that these pulses may cause the IGBT's to operate outside their safety margin.

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