Measurement and Optimal Measurement of a Non-linear Solenoid Valve

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Final Project Presentation - EE5630

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Outline of the Presentation

- Introduction
- Background and Motivation
- Problem Formulation
- Dynamics and Cost Function
- Analysis and Simulation
- Conclusion

Introduction

What is a Solenoid Valve?

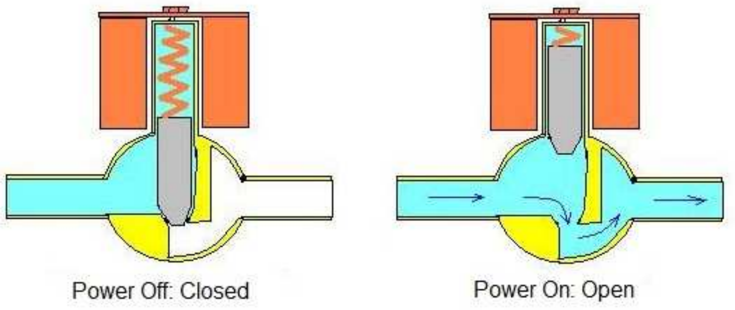


Figure: A Solenoid Valve

Background and Motivation

Solenoid Valves: Possible Applications

1. Hydraulics for actuation
2. On/Off fluid flow for mixing
3. Pressure application for injection molding

- Fast switching is often desirable
- Fast switching can cause a non-linear response
- Our objective is to have a fast, linear response with a minimized control input

Problem Formulation

Methods of Acquiring Dynamics

1. Data Sheet
2. Analyzing the physics of the mechanisms within the system to analytically solve for the differential equations
3. Physically test the input and output of a system using sensors

Method 3 was used for this project

Solenoid Valve: Modeling

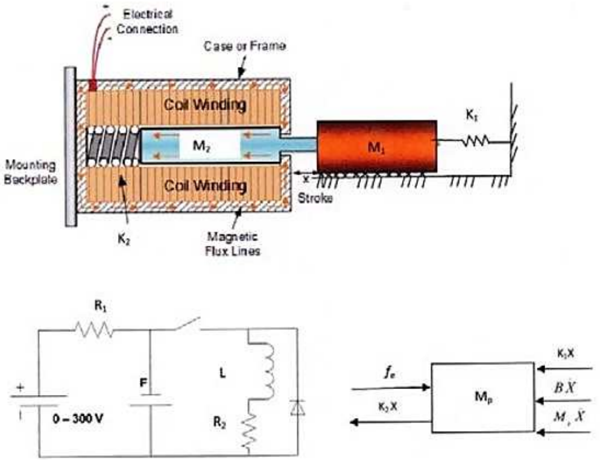
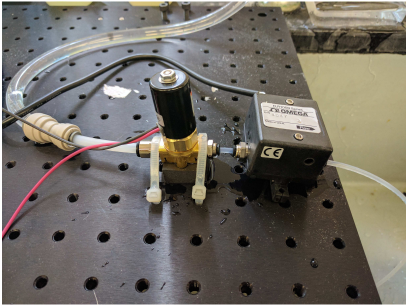
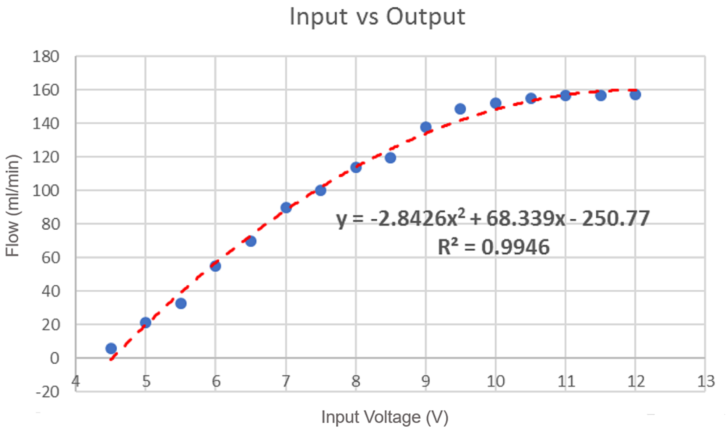


Figure: Solenoid Valve With Equivalent Circuit and Free Body Diagram

Testbed

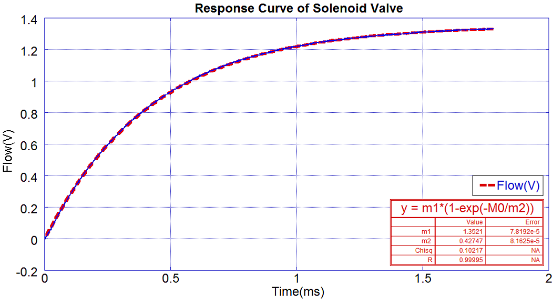
- A testbed was assembled to record the solenoid's response to a step input of 12V





- The curve is nonlinear
- Linearizing the transfer function was found to not dramatically affect the final output
- For simplicity it was assumed to be linear.

Response Curves



- The response to a step input had the same form as a charging capacitor, a curve fit was applied using the equation of a charging capacitor

Dynamics of the System

The derivative of equation (1), equation (2) is our first state equation

Charging Capacitor Model

$$Q = Cu(t)(1 - e^{\frac{-t}{RC}}) \tag{1}$$

$$dx = \frac{u(t)}{R}(e^{\frac{-t}{RC}}) \tag{2}$$

Cost Function

- Goal was to follow a predetermined line to linearize response and to minimize control effort
- Both a tracking function and a minimum control effort component were added to the cost function shown in Equation (3)

Cost Function

$$J = \int_{t_o}^{t_f} ||x(t) - r(t)||_Q^2 + u(t)^2 dt \qquad (3)$$

Optimal Control Approach

Pontryagin's was used due to the non-linearity of our system. By definition, the control u* causes the functional J to have a relative minimum if:

Pontryagin's Minimum Principle

$$J(u) - J(u*) = \Delta J \geq 0 \tag{4}$$

Optimal Control Approach

- The Hamiltonian(5) was used to determine the state equation (7) co-state equation(8) and the necessary condition for u*

Equations

$$H = g + p[a] \tag{5}$$

$$H = (x - .7493)^2 + u^2 + p\left(\frac{100000ue^{\frac{-100000t}{42747}}}{42747}\right) \tag{6}$$

Necessary Condition Equations

$$\frac{\partial H}{\partial p} = \dot{x} \; = \frac{100000ue^{\left(\frac{-100000t}{42747}\right)}}{42747} \tag{7}$$

$$\frac{\partial H}{\partial x} = \dot{p} = 2x1.5t \tag{8}$$

$$\frac{\partial H}{\partial u} = 2u + \frac{-100000pe^{\left(\frac{-100000t}{42747}\right)}}{42747} \tag{9}$$

- The necessary condition for u* can be determined setting equation (9) equal to zero and solving for u
- The analytical solutions to these equations were cross checked in Matlab by using a symbolic solver

- Once the state and co-state equations were determined, MATLAB function bvp4c was used to determine x and p
- These values were then substituted back into u* shown in equation (9)

u*

$$u^* = \frac{-100000pe^{\left(\frac{-50000t}{42747}\right)}}{42747} \quad (10)$$

Initial Simulation

- The first simulation had zero weighting added to the cost function is equation (3)
- The minimum control effort component of the cost function seems to be dominant
- Weighting will be introduced in future trials

Initial Simulation Results

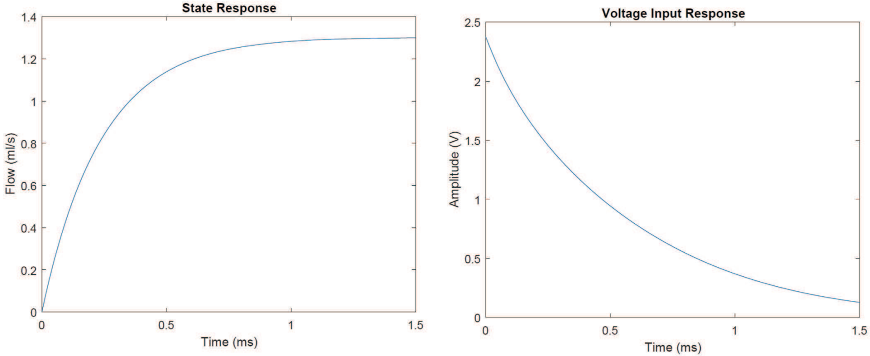


Figure: Zero Weight Response

Weighting

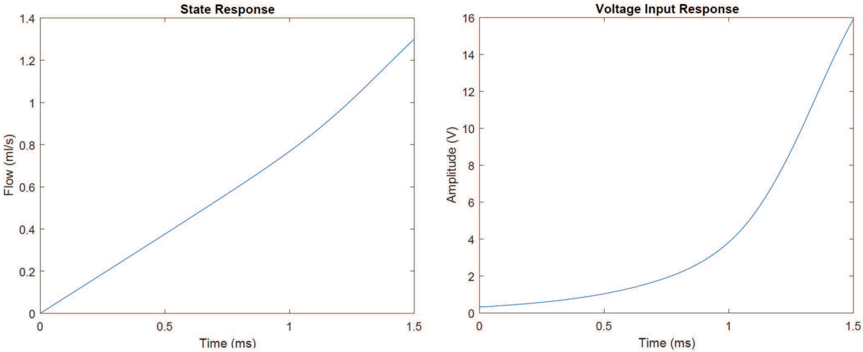


Figure: 5000 Weight Response

- A weighting factor of 5000 was added to the tracking function component, but ended up being too high

Weighting

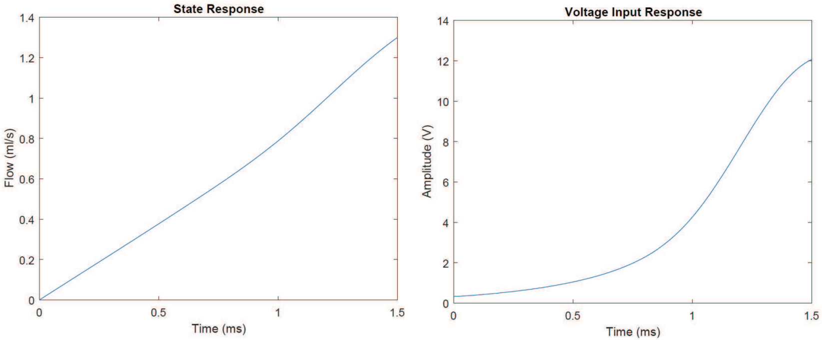


Figure: 2750 Weight Response

- After various trials a weighting factor of 2750 was used and the response was as expected

But Wait There's More!!!

Figure: Billy Mays

Physical Test

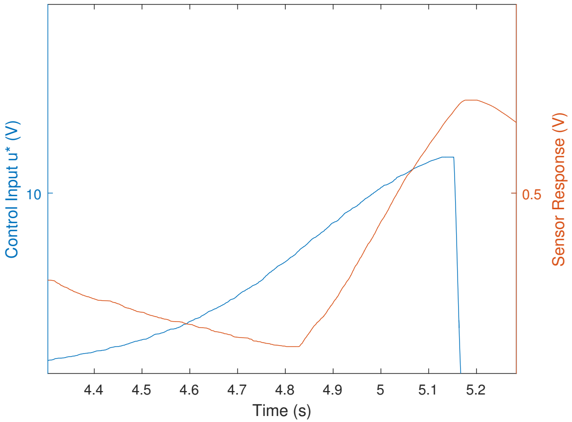


Figure: u* input (V) and Sensor Response (V) vs. Time (s)

Physical Test cont.

- The optimal control input u* was applied to the actual solenoid valve
- The sensor's response was linear, confirming simulated results in real application

Limitations of the work

- Optimal control limited by sensor speed
- Sensors response is linearized
- A faster, more accurate sensor will enhance optimal control's effects

Conclusions

- Physical testing was successful and confirmed the control calculated constrains the flow to a linear path
- Error of the final state was approximately 1% which is reasonable for most applications that require a linear flow response

Future Work

- Apply nonlinear transfer function to dynamics to eliminate error
- Integrate higher quality flow sensor for accurate data acquisition
- Calibrate pressure drop between two pressure sensors for accurate flow reading

Thank you!

Questions?