# A Novel PID Controller for Pneumatic Proportional Valves with Hysteresis

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**Abstract- A novel Modified PID (MPID) controller is developed to control and minimize the effect of hysteresis in Pneumatic proportional valves. It consists of four parts: a Proportional-Integral-Derivative (PID) controller, a Feedforward term, an Anti-Windup mechanism, and a Bang-Bang controller. The result is a unique Modified PID (MPID) control scheme that demonstrates better command following and disturbance rejection qualities than a Conventional PID (PID + Feedforward + Antiwindup) scheme.**

**The control scheme is simulated based on an empirical model derived from actual valve measurement data. The results show that the proposed MPID controller provides better step response, command following, and greater bandwidth than conventional methods. Furthermore, it is demonstrated that the robust control is achieved in the presence of significant dynamic variations in the valve. In particular, it is shown that satisfactory performance can be maintained when the valve hysteresis characteristics are varied by as much as 30%.**

## I. Introduction

Pneumatic valves are used extensively in various industries today. Not only are they used in process control and medical assistance equipment, they are also the basis for the foundation brakes of trucks and buses all over the world. One of the major challenges in controlling pneumatic valves is the ability of a control system to deal with hysteresis. This non-linearity is present due to coulombic friction, temperature, and manufacturing tolerance stackup of the valves. A closed-loop control system utilizing a PID controller is often employed to attempt to control these valves.

The PID controller is widely used across the industry. It is easy to implement and relatively easy to tune. On the other hand, the simplicity of the controller puts limitations on its capabilities in dealing with complex control problems, such as the hysteresis problem. In this paper, the limitations of traditional PID are discussed and a new form of PID is proposed. The proposed method compensates for the hysteresis in a nonlinear fashion to achieve acceptable step response and steady state error characteristics.

While pneumatic valves are used in various industries, the most challenging application is that found in the Heavy-Duty truck and bus. Pneumatic valves in this industry have to be able to operate reliably under harsh environmental conditions. Industry standard has been established that detail the vibration, humidity, thermal, salt spray, and temperature extremes these valves must operate within. This makes the design of valve control systems a very challenging task.

The main difficulty in controlling industrial quality pneumatic valves stems from the inherent hysteresis. This is particularly troublesome since the environment has a direct bearing on the characteristics of hysteresis in general. Hysteresis tends to vary with temperature, friction of internal components, and manufacturing tolerance stackup. Therefore, it is not surprising to see a significant difference in characteristics from valve to valve. In fact, differences on the order of 25% are not uncommon in practice.

### A. *Summary of the new results*

To resolve the difficulty brought by the presence of hysteresis, a Modified PID control scheme is proposed and tested in simulation using an empirical model that reflects the actual valve dynamics. The performance of the Conventional PID and the novel MPID controller is compared in Figure 1. As can be seen, the MPID controller has faster rise time and shorter settling time during a step function stimulus. It will be further illustrated that the Modified PID also outperforms the conventional controller for command following; it tracks the desired setpoint more accurately, and exhibits a wider bandwidth than the conventional method.

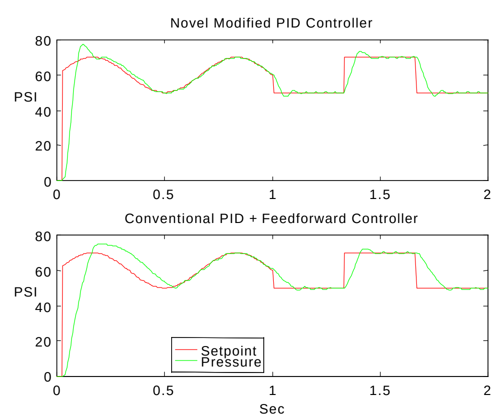


Figure 1. Comparison of MPID and Conventional PID

### B. *Characteristics of the Proportional Modulator Valve*

The proposed MPID will be used to control a proportional modulator valve. This valve is controlled by a 200 Hz PWM signal. The valve is connected to an air supply tank of 145 PSI and is at maximum opening at a 100% PWM value. At zero percent the valve is in the closed position.

A computer simulation model describing the behavior of this valve has been developed by Knorr Bremse SfN of Munich Germany. This file was converted to a Simulink S-Function and is used in this paper as the plant model. The model is based on empirical measurements and serves to provide a plant that mimics real world components and is particularly challenging for command following under increasing frequencies.

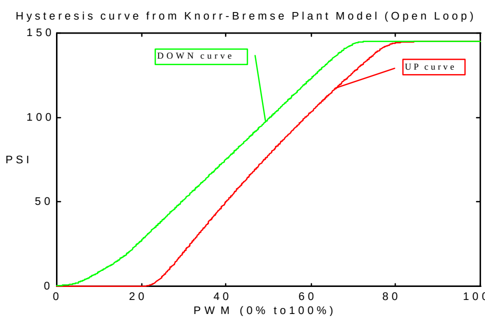

Figure 2. Hysteresis curve of plant model

In order to understand the characteristics of the valve, a control signal is applied to generate an open loop response. The input signal was ramped from 0% to 100% in five seconds, then from 100% back to 0% in another five seconds. The response to these stimuli has been superimposed on the same graph and results are depicted in Figure 2 above. Increasing PWM is indicated by the UP side of the curve, and decreasing PWM is indicated by the DOWN curve.

## II. THE DEVELOPMENT OF MPID

In general, a PID controller takes as its input the error (e or Err), or the difference, between the desired setpoint and the output (e=R-y). It then acts on the error such that a control output, u, is generated. Gains Kp, Ki, and Kd are the Proportional, Integral and Derivative gains used by the system to act on the error, integral of the error, and derivative of the error respectively.

It should be noted that the output of the PID controller is defined as u, and the actual control input to the plant is uu. In real world, these two signals are often different. The saturation block limits u to the real values of 1 to 999 (.1% to 99.9% PWM), corresponding to full-off or full-on position of the valve.

The Proportional plus Integral plus Derivative (PID) control action can be expressed in the time domain as:

$$u(t) = K_p e(t) + \frac{Kp}{T_i}\int_0^t e(t)\,dt + K_p T_d \frac{de(t)}{dt} \tag{1}$$

Taking the Laplace transform of (1) yields:

$$U(s) = K_p E(s) + \frac{K_p}{T_i s} E(s) + K_p T_d s E(s) \tag{2}$$

and the resulting PID controller transfer function of:

$$\frac{U(s)}{E(s)} = K_p\left(1 + \frac{1}{T_i s} + T_d s\right) \tag{3}$$

A typical real-time implementation of a digital PID controller can be expressed as:

$$u(k) = K_p e(k) + ui(k-1) + \frac{K_p T}{T_i} e(k) + K_p T_d \frac{(e(k) - e(k-1))}{T} \tag{4}$$

While PID is an effective controller for a linear system, it is not capable of controlling a nonlinear system with hysteresis, alone. In practice, it is necessary to include a feedforward term to the PID output so that the controller can react to the error more quickly in order to bring the plant to the desired setpoint. The feedforward design is basically an open loop controller that is based on the model of the plant. It helps to reduce the burden of the closed-loop PID controller.

A typical industry practice for the feedforward term involves approximating the input-output relationship of the plant and using the approximation to generate a reasonable control signal to achieve the desired output. Figure 3 in the Appendix depicts the linear estimates for the UP and DOWN curves for the plant model discussed above, while Figure 4 shows the block diagram of PID with feedforward.

The feedforward contribution relies on the linear estimates of the UP and Down curves in Figure 3 as well as the sign of the error. It compensates the input signal to the valve such that the hysteresis effects of the valve are nullified.

### A. *The Addition of an Antiwindup Term*

To prevent the integrator from winding up, an anti-windup mechanism can be implemented within the PID controller as a subtractive term from the integral contribution. This mechanism usually includes a deadzone, DZ, and can be represented by:

$$\begin{aligned} &Integ.Term = (Integ.Term - Antiwindup) \\ &Where,\ Antiwindup\ is: \\ &Antiwindup = \begin{cases} 0, -DZ < PID < +DZ \\ K * (PID - DZ) \end{cases} \end{aligned} \tag{5}$$

The antiwindup term can be implemented in other ways, and the mechanism is sometimes referred to as Integrator Reset. This term is illustrated in Figure 5 as Antiwindup.

### B. *The Addition of Bang-Bang Controller Term*

Ideally, the valve should have the absolute minimum rise time for any pressure application so that the control system will have a good step response. To this end, it was shown that an On-Off, or Bang-Bang, controller is the best mechanism for achieving minimal rise-time[5].

Based on the Bang-Bang control principle [5], the minimum-time[1] control law has the property that each control variable is always at either its upper or its lower bound. That is, if it is desired to bring the state of the process back to the origin as fast as possible, the largest available effort in the proper direction must be used. Therefore, in Bang-Bang Control, the controller output is no longer a smooth signal proportional to the error. It is always saturated.

With the addition of a Bang-Bang term, shown in (6) and Table I, the controller can be described as a PID plus Feedforward plus Bang-Bang plus Antiwindup controller, or more simply for this paper, the Modified PID, or MPID controller. Figure 6 shows the addition of the Bang-Bang controller to the diagram. The output of this block has the affect of a full-on or full-off actuation of the valve and acts as a dominant term in the transient response.

It is important to note that the on and off type of control always results in excessive oscillation when the pressure is close to the setpoint. For this reason, the Bang-Bang term is set to zero for small errors. Furthermore, this term is also made a function of dR/dt, as shown in Table I, which is the rate of change for the pressure setpoint. The values in Table I were obtained experimentally. The idea is that the effects of the Bang-Bang term should be limited when the setpoint is changing slowly. This ensures the smooth following of the setpoint. But when the pressure setpoint is changing fast, the control action must be drastic for the output pressure to keep up with it.

## III. SUMMARY OF SIMULATION RESULTS

The MPID and conventional PID controller are compared extensively under various conditions, such as step response, sinusoidal input response at different frequencies. Furthermore, the robustness of the controllers is compared as the hysteresis of the valve varies. In general, the MPID demonstrates superior performance over the conventional PID. For example, as the valve hysteresis varies, the MPID provides much tighter control than the PID as shown in Figure 7. Interested readers are referred to [10] for more details of the control design and simulation results.

$$K * Bang - Bang = \begin{cases} 0, & \begin{pmatrix} |err| \le 3PSI \\ and \\ |\frac{dR}{dt}| < .5 \end{pmatrix} \\ 999, & err > 1.5PSI \\ -999, & err < -1.5PSI \\ 0, & err = 0 \end{cases} \qquad (6)$$

Where K is a gain based on the range of dR/dt as indicated in the Table below:

*TABLE 1BANG-BANG RANGE DEPENDENT ON DR/DT AND ERR*

| | \|Err\| <= 3 PSI<br>\|dR/dt\| < .5<br>Bang-Bang= 0 | \|Err\| > 3 PSI<br>and<br>dR/dt < 50 | \|Err\| >= 3 PSI<br>and<br>dR/dt >= 50 |
|---|---|---|---|
| Err ∈ ( 0, 20] | *The Weights* | K = 0.03 | K = 1.00 |
| Err ∈ (20, 40] | *are ignored* | K = 0.10 | K = 1.00 |
| Err ∈ (40, 60] | *in this regio* | K = 0.30 | K = 1.00 |
| Err ∈ (60, 80] | *since the Bang-Bang terr* | K = 0.70 | K = 1.00 |
| Err ∈ (80,100] | *is equal* | K = 0.80 | K = 1.00 |
| Err ∈ (100,120] | *to zero.* | K = 0.90 | K = 1.00 |
| Err ∈ (120, ∞) | | K = 1.00 | K = 1.00 |

## CONCLUSION

A Conventional PID (PID + Feedforward + Anti-windup) controller was investigated as a means to control a class of pneumatic Proportional Modulator relay valves. A Simulink model based on an empirically generated model of the relay valve was used for the plant. Then, a nonlinear mechanism (Bang-Bang) was added to the existing PID controller to obtain the MPID scheme. It was shown that this new control system increased the bandwidth of the system, and improved the step and command following response of the system. Furthermore, it was demonstrated that the addition of the Bang-Bang controller greatly enhanced the robustness of the system.

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## Appendix

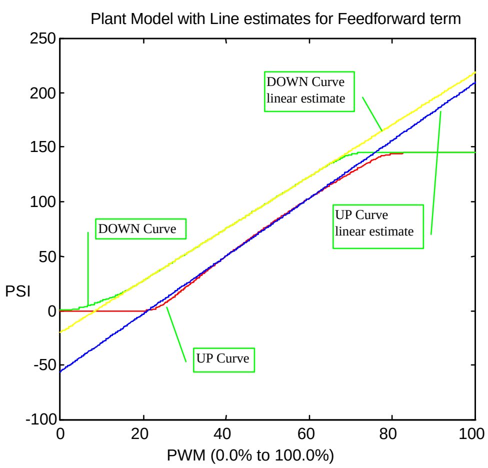


Figure 3. Plant Model with Line Estimates for Feedforward term

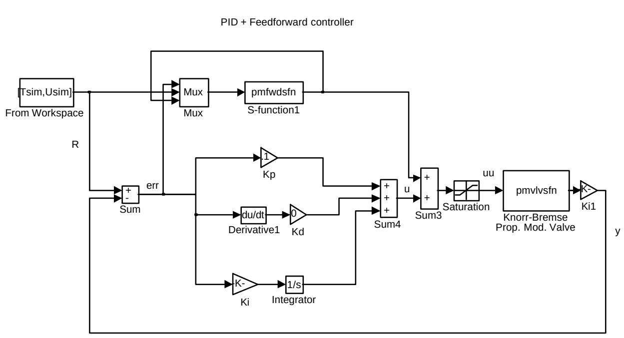


Figure 4. PID plus Feedforward block diagram

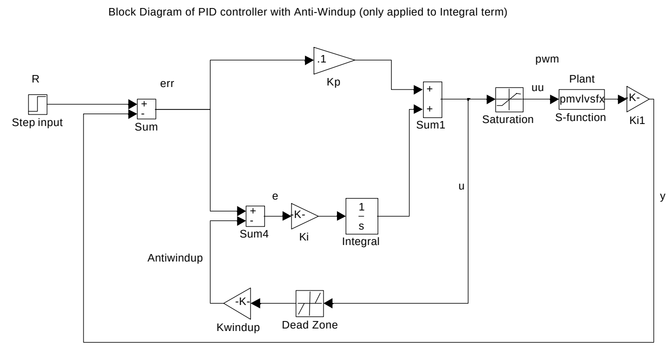


Figure 5. Block diagram of PID plus an Integrator Anti-Windup term

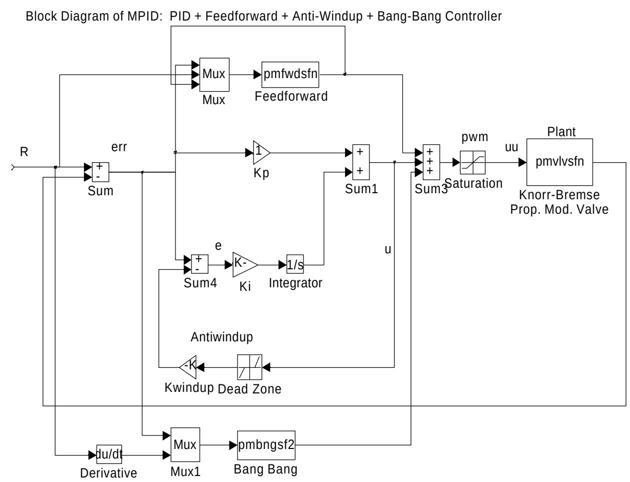


Figure 6. Block diagram of a MPID controller

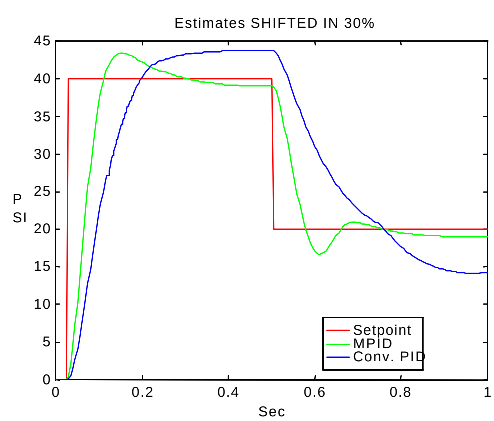


Figure 7. Comparison of conventional PID and MPID as the valve hysteresis varies by 30%