Practical robust control using Self-regulation Nonlinear PID controller for pneumatic positioning system

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Abstract- This paper investigates the robustness of the pneumatic positioning system controlled by Self-regulation Nonlinear PID (SNPID) controller. This controller is executed by utilizing the characteristic of rate variation of the nonlinear gain that are readily available in Nonlinear PID (NPID) controller. A Self-regulation Nonlinear Function (SNF) is used to reprocess the error signal with the purpose to generate the value of the rate variation, continuously. Simulation and experimental tests are conducted. The controller is implemented to a variably loads and pressures. The comparison with the other existing method i.e. NPID and conventional PID are performed and evaluated. The effectiveness of SNPID + Dead Zone Compensator (DZC) has been successfully demonstrated and proved through simulation and experimental studies.

Keywords—pneumatic positioning system; NPID; self-regulation nonlinear function; dead-zone compensation; robustness

I. INTRODUCTION

Pneumatics is a branch of technology that deals with mechanical properties of gases such as pressure and density. They are categorized under fluid power control and apply the principles of using compressed gas as a source of power to perform a variety of tasks. Its offer several advantages such as low cost, simple to maintain, high power to weight ratio, fast motion, free from overheating and reliable[1]. Due to these advantages, this actuator continues to generate significant research interests and it has been promoted as an alternative to hydraulics and electric servo motors in many automated tasks. However, it exhibits high nonlinearities due to high friction forces, compressibility of air and dead band of the spool movement in the valve[2]. These nonlinearities make an accurate position difficult to achieve, and it requires an appropriate controller for better performance.

In early 1900s, due to the difficulty of obtaining a good performance, the use of this actuator has greatly limited in many applications. Thus, research on this component is rarely performed for decades until there is a demand to be applied in the automation industry circa 1950s[3]. Research on pneumatic positioning control has increased in the 1990s when many control techniques have been examined on the system such as PID control, PD plus, sliding mode control, robust control, adaptive control, and PWM control [4-6]. Although the conventional PID controller is not suitable for the systems with high nonlinearity, but it is still popular with the idea of modification as a study conducted by[7-9]. This controller is widely applied in industries compared to the other techniques due to its good characteristics and easy to implemented as well as mature in theoretical analysis[10].

In[11], an approach to alter third-order system for pneumatic actuator into three first-order systems connected in series is presented. In this approach, the original integrator plant transfer function of the system was modified by inserting an analogue feedback with proportional gain. The proportional gain is tuned until the greatest value of gain which leads the system to the verge of the appearance of overshoot is obtained. In the next two years, a modification PID controller with nonlinear compensation and acceleration feedback based on time delay minimization and position compensation algorithm was introduced by [12] to achieve accurate position control. The advanced control strategies such as fuzzy logic control, adaptive control, neural network and others were aggressively investigated and applied on the early of 2000s onward. However, in the last decade many researchers found that the techniques that integrate with PID controller are more practical in pneumatic positioning system compared to another new method. It referred to the increasing number of publications written by [13-21] and amongst others.

This paper deals with the investigation on the robustness of the pneumatic actuators which controlled by the novel Self-regulation Nonlinear PID (SNPID) controller that had been published in the previous work [22]. The robustness of the

system is examined based on the variation of load and pressure for both increasing and decreasing of these items. The Dead Zone Compensation (DZC) is added to the system, and the consequence to the system is observed. The experiments are performed to confirm the capability of this controller. The comparisons with the existing methods including PID and NPID controller are performed based on transient and steady-state performance.

This paper is organized as follows: In section II, mathematical modelling of the pneumatic actuator is described. In section III, an SNPID controller is described. In section IV, a design of DZC is provided. The simulated and experimental results using MATLAB/SIMULINK are described in section V. Finally, section V1 contains some concluding remarks.

II. SYSTEM MODEL

The system under consideration consists of 5/3 proportional directional control valve, double-acting with double rod cylinder, pressure sensors, displacement transducer, data acquisition system, PC and mass payload as shown in Fig. 1.
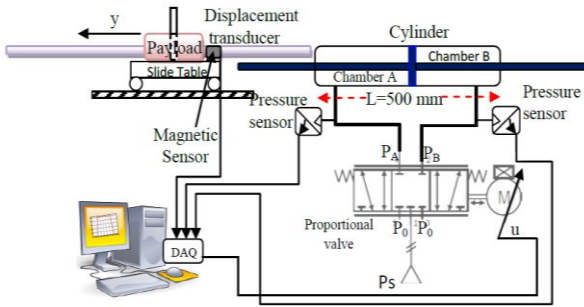

Fig. 1. Pneumatic Positioning System Test Rig

The transfer function of the system is obtained using System Identification. For this purpose, 2000 data points representing the input and output signal of the open loop system were collected with a sampling time of 0.01 second. A state space model as shown in (1) and (2) is used as a model structure of the system.

$$x(t+Ts) = Ax(t) + Bu(t) + Ke(t) \qquad (1)$$

$$y(t) = Cx(t) + Du(t) + e(t) \qquad (2)$$

where, $A \in R^{nxn}$, $B \in R^{nxm}$, $C \in R^{lxn}$ and $D \in R^{lxm}$ are the matrices of the system. $e(t)$ is the vector represent the difference between the measured output and the predicted output of the model. While $x(t) \in R^n$, $y(t) \in R$, $u(t) \in R^m$, and $K \in R^{n \times m}$ represent the state-vector, measured output, measured input signal and noise, respectively. The estimation of the values of the parameters is performed using the Prediction-Error Minimization (PEM) technique within MATLAB. Through this method, the parameters are calculated by minimizing a cost function of the prediction errors, giving;

$$V_N(\theta, Z^N) = \frac{1}{N} \sum_{k=1}^{N} e^2(k, \theta) \qquad (3)$$

Where Z^N and N denotes the set of data and number of data samples, respectively. For linear systems the error can be expressed as;

$$e(k) = H^{-1}(\theta)[y(k) - G(\theta)u(k)] \qquad (4)$$

Therefore, the parameter estimation can be obtained through (3) and (4) by minimizing V_N as follows;

$$\hat{\theta}_N = \arg\min_{\theta} \frac{1}{N} \sum_{k=1}^{N} H^{-1}(\theta)[y(k) - G(\theta)u(k)]^2 \qquad (5)$$

Through Zero Order Hold (ZOH) conversion method, a continuous transfer function is defined as:

$$Gp(s) = \frac{-0.507s^2 + 6.385s + 92.490}{s^3 + 15.740s^2 + 85.530s + 0.389}$$

III. CONTROLLER DESIGN

In general, the transfer function of PID controller in a series with noise filter is given by:

$$\frac{U_{PID}(s)}{E(s)} = \left(k_p + \frac{k_i}{s} + \frac{k_d s}{(T_f s + 1)} \right) \qquad (6)$$

The proportional gain, k_p and integral gain k_i is used to improve the rise time and eliminate the steady state error, respectively. Meanwhile, the derivative gain, k_d can give the effect of increasing the stability of the system by improving the transient response and reducing the overshoot.

In any control system design, stability is the first criterion that needs to be considered. In order to maintain the stability of the system, the conditions as written in (7) must be complied.

$$|L(j\omega_{BT})| < 1 \qquad (7)$$

Where;

$|L(j\omega_{BT})|$ -magnitude of the open loop system,

Besides, the speed of the response is one of the criterions that need to be considered to obtain the optimal performances. It leads to considering the bandwidth frequency of the system. In general, the speed of the response is increased with respect to the increasing of bandwidth. However, it involves a trade-off between speed and robustness of the response, and high bandwidth makes the system sensitive to the noise. Thus, in order to provide a good consequence in a wide range of performance including stability, speed and robustness, the design should correspond to various criteria including gain margin, phase margin, gain crossover frequency and maximum sensitivity. The required maximum peak for the sensitivity function should be less than or equal to 6dB.

In order to ensure the optimum performance to be acquired, several simulations based on different Gain Margin (GM) and Phase Margin (PM) were conducted as depicted in Table 1. Based on these simulation results, the optimum value of GM and PM are 15.7 dB and 41.9° at frequency 0.851 Hz and 0.289 Hz, respectively. These values provide an appropriate trade-off between speed performance and robustness. It is clearly can be seen from Table 1, even the rise time was decreases the performance of the overall system become worst in terms of robustness when PM is below than 30°. Besides, the numbers of oscillation are increases and explicitly tend to reduce the stability of the system. According to [23], in practice for well-tuned system the value of GM and PM should be between 6 dB to 20 dB and 35° to 80°, respectively. However, as can be observed in Table 1, by allowing the value of GM more than 20 dB may increase the system robustness. However, due to the waterbed effect, it has affected the system performance in terms of speed.

TABLE 1. PERFORMANCE OF THE SYSTEM WITH RESPECT TO GM AND PM

Gm	Pm	tr (s)	ts (s)	Number of oscillation	Robustness criterion
27.3	71.1	2.37	3.83	-	√
23.7	63.3	1.47	4.30	-	√
20.7	55.7	1.05	3.55	< 1 cycle	√
18.8	50.6	0.87	4.47	< 1 cycle	√
15.7	41.9	0.65	3.81	< 1 cycle	√
11.7	30.7	0.46	5.05	2 cycle	√
7.7	19.7	0.34	6.56	3 cycle	×
4.7	11.8	0.27	9.34	6 cycle	×
1.25	3.12	0.21	> 30	> 10 cycle	×

Thus, the nonlinear gain, $k_x(e)$ which bounded in the sector $0 \le k_x(e) \le k(e_{max})$ as indicated in (8) is used to increases the performance of the system. This gain represents the continuous dynamic nonlinear function. This function is then combined in cascade with PID controller.

$$k_x(e) = \frac{\exp(\alpha_i e) + \exp(-\alpha_i e)}{2} \tag{8}$$

where:

$$e = \begin{cases} e & |e| \le e_{max} \\ e_{max}\, sign(e) & |e| > e_{max} \end{cases}$$

α_i – rate variation of nonlinear gain
e_{max} – range of variation

The value of nonlinear gain $k_x(e)$ is automatically varied depends on the value of α_i that is on-line generated using (9). Fig. 2 shows the block diagram of the system with SNPID controller.

$$\frac{\alpha_i(s)}{e(s)} = \frac{d}{ds}\left| \frac{\delta}{\beta s + 1} \right| \tag{9}$$
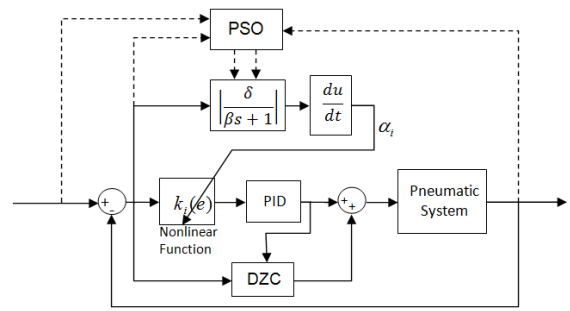

Fig. 2. Self-regulation Nonlinear PID (SNPID) controller

The design parameters are determined by identifying the relationships between δ and β in order to produce the maximum value of rate variation (α_i) with exponential decay. It performed using Particle Swarm Optimization (PSO) technique. Details on this technique were explained in [22]. Table 2 indicates the results of δ and β through this optimization technique. The relationships between δ and β can be plotted as shown in Fig. 3. Thus, the equation as expressed in (10) can then be applied to determine the value of δ and β.

TABLE 2. PARAMETER DETERMINATION VIA PSO

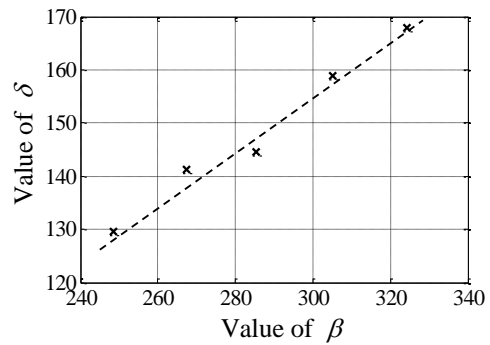|	Op1	Op2	Op3	Op4	Op5
δ	167.9	141.2	158.9	144.5	129.51
β	324.4	267.5	305.2	285.3	248.53
$\delta : \beta$	0.518	0.528	0.521	0.506	0.521

Fig. 3. Relationship between δ and β

$$\delta = 0.51\beta \tag{10}$$

The rate variation (α_i) is designed to provide a certain value of nonlinear gain at the beginning for the purpose to overcome the static friction. This rate variation is then decreasing starting from this value and ending at 0 where the steady state response is achieved. For better interpretation, it can be elaborated through the following derivation;

From (9), let;

$$G_{\delta,\beta}(s) = \frac{\delta}{\beta s + 1}$$

$$= \frac{\delta/\beta}{s + 1/\beta}$$

Considered impulse response represents the error signal, thus;

$$g_{\delta,\beta}(t) = L^{-1}\left[G_{\delta,\beta}(s)\right] = 1 - \frac{\delta}{\beta}e^{-\frac{t}{\beta}}(t) \qquad (11)$$

Perform differential of (11);

$$\alpha(t) = \frac{d}{dt}\left[g_{\delta,\beta}(t)\right] = \frac{\delta}{\beta^2}e^{-\frac{t}{\beta}}(t) \qquad (12)$$

Based on the initial value theorem;

$$\lim_{t \to 0}\left|\alpha(t)\right| = \lim_{t \to \infty}\left|\frac{\delta}{\beta^2}e^{-\frac{t}{\beta}}\right| = \frac{\delta}{\beta^2} \qquad (13)$$

Based on the final value theorem;

$$\lim_{t \to \infty}\left|\alpha(t)\right| = \lim_{t \to \infty}\left|\frac{\delta}{\beta^2}e^{-\frac{t}{\beta}}\right| = 0 \qquad (14)$$

IV. DEAD-ZONE COMPENSATION (DZC)

In this section, a similar compensator as in [22] is used to overcome the dead-zone nonlinearity. In practice, the width of dead-zone is unknown. Thus, the compensator as illustrated in Fig. 4 is employed to offset the deleterious effects of dead-zone. Where, C(s) represent the controller while G(s) and DZC are pneumatic actuator and dead-zone compensator, respectively.
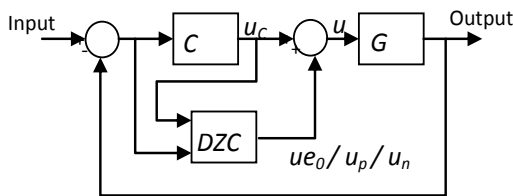

Fig. 4. System block diagram with dead-zone compensator

It is implemented by using the following rules:

$$if \ \left|e\right| \le e_d \ then \ U_{DZC} = U_{e0}$$

$$if \ \left|e\right| > e_d \ And \ U > 0 \ then \ U_{DZC} = u_P$$

$$if \ \left|e\right| > e_d \ And \ U < 0 \ then \ U_{DZC} = u_n$$

V. RESULTS AND DISCUSSION

Simulation and experimental validation are performed to evaluate the performance of the pneumatic positioning system controlled by SNPID. It is examined using the different step input and tested to various mass of the load and pressure. The controller is designed for the system with a nominal payload mass of 3.2 kg and 8.4 kg. The difference between the nominal and other mass of the payload were tested to illustrate the robustness of this controller. The performance of this technique is compared to the other techniques namely conventional PID and NPID controller. The parameters of the proposed controller including SNF and other parameters are tabulated in Table 3. The parameters of the PID should be determined earliest before the other parameters can be obtained.

TABLE 3: PARAMETERS OF THE CONTROLLER

Control strategies	Control Parameters		
	Parameter	*Abbreviation*	*Value*
PID	Proportional Gain	Kp	2.099
	Integral Gain	Ki	9.56×10^{-3}
	Derivative Gain	Kd	0.035
	Filter	N	12.207
SN-Function	Param 1	δ	129.51
	Param 2	β	248.53
	Variation of Error	e_{max}	2
Dead-zone compensator	Control value in the range of desired e_{ss}	u_{e0}	0.01
	+ve dead-zone compensation	u_p	0.5
	-ve dead-zone compensation	u_n	-0.65
	Desired e_{ss}	e_d	0.005

Fig. 5 demonstrates the simulated result of the output response obtained from the system controlled by SNPID, PID and NPID controller. The result indicates that these controllers are able to follow the input with different position and direction. Though, it can be seen that the SNPID offer faster response with lower steady-state error compared to the other methods. The steady-state error for the system with NPID is close mimics the result obtained by the system with SNPID controller. However, it provides the slower response compared to the others. For a system with PID controller, the performance is doggerel compared to other due to the presence of overshoot that can reduce the system robustness. In order to validate the performance of the SNPID controller, the result from the simulation is compared to the result obtained from the real-time system. As can be seen from Fig. 6, the response obtained based on experimental is quite similar with the simulation.

The ability of the SNPID controller to compensate the system when there are changes occurs in the load and pressure is then investigated. The performance is analyzed for both conditions in the case of the load/pressure is increasing or decreasing. The measurement of the performance is based on the distance of 200 mm. Comparison with the other methods are performed as a performance benchmark. The details

performances based on the experiments for all cases are tabulated in Table 4, 5, 6 and 7.
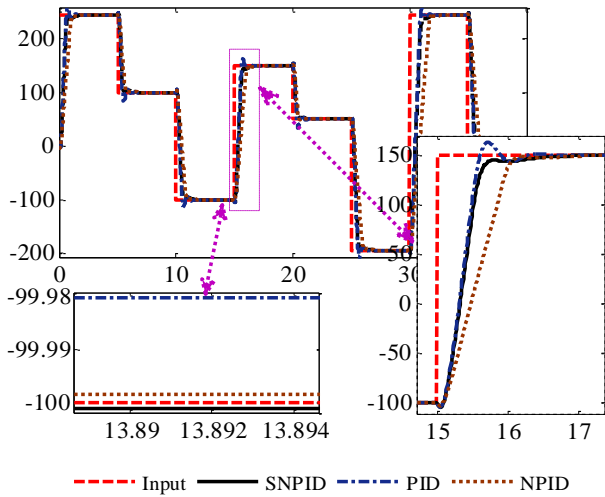

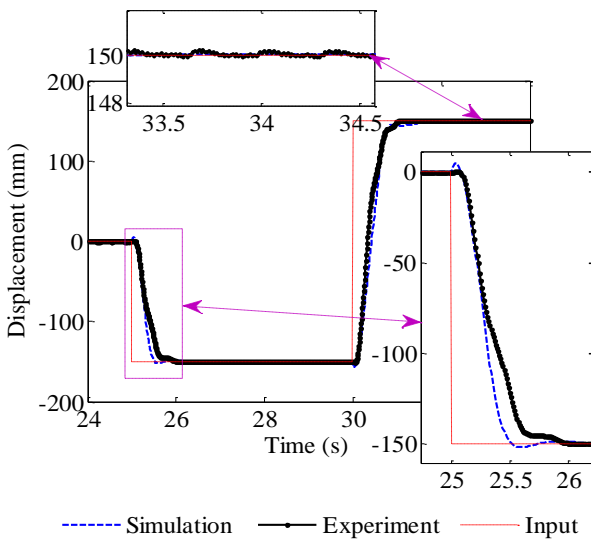Fig. 5. Simulation result for different controller

Fig. 6. Simulation and Experimental result for SNPID

TABLE 4: PERFORMANCE OF THE SYSTEM FOR M=3.1 KG WITH NOMINAL LOAD M=8.4 KG

Performance	Controller		
	SNPID+DZC	*NPID+DZC*	*PID+DZC*
Settling Time (t_s)	0.659	1.524	1.123
Rise Time (t_r)	0.314	1.268	0.317
Overshoot (%OS)	0	0	7.973
Steady-state error (e_{ss})	0.043	0.112	0.267

TABLE 5: PERFORMANCE OF THE SYSTEM FOR M=13.5 KG WITH NOMINAL LOAD M=8.4 KG

Performance	Controller		
	SNPID+DZC	*NPID+DZC*	*PID+DZC*
Settling Time (t_s)	0.679	1.803	1.403
Rise Time (t_r)	0.241	1.455	0.306
Overshoot (%OS)	0	3.375	20.869
Steady-state error (e_{ss})	0.046	0.118	0.269

TABLE 6: PERFORMANCE OF THE SYSTEM WHEN PS IS REDUCED TO 0.45 MPA

Performance	Controller		
	SNPID+DZC	*NPID+DZC*	*PID+DZC*
Settling Time (t_s)	0.797	1.612	1.115
Rise Time (t_r)	0.336	1.173	0.334
Overshoot (%OS)	0	0	8.081
Steady-state error (e_{ss})	0.0162	0.021	0.196

TABLE 7: PERFORMANCE OF THE SYSTEM WHEN PS IS INCREASED TO 0.75 MPA

Performance	Controller		
	SNPID+DZC	*NPID+DZC*	*PID+DZC*
Settling Time (t_s)	0.699	1.276	1.321
Rise Time (t_r)	0.340	0.636	0.325
Overshoot (%OS)	0	3.304	19.992
Steady-state error (e_{ss})	0.019	0.025	0.367

The result indicates that the SNPID and NPID controller are more robust than PID. It can be seen that, when the moving mass is increased from 8.4kg to 13.5 kg, the overshoot for the PID controller is significantly increase. It becomes more aggravated if the mass is increased and ultimately affected the stability of the system. The same situation occurs when the pressure is increased. While, the system with SNPID controller has successful to keep better performance. The consistency of the performance for all cases indicates that this controller is less sensitive to the changes of load and pressure.

VI. CONCLUSION

In this paper, a robustness of the SNPID controller was investigated. Initially, the performances of the system with this controller are examined through simulation. It has been conducted for a different distance and direction to ensure the consistency of the performance. Experiments to the real plant are performed for validation purposes and found only slight distinction between them in the transient part. Subsequently, the robustness of the system was investigated. It has been tested by decreasing and increasing the load. Moreover, the effect caused by variation of pressures to the system performance is also examined. The system with SNPID shows

the superior performance in terms of accuracy, speed and robustness compared to another method that are examined in this research. Besides, it provide the lower steady state error and able to maintain the response without overshoot.

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