Research Article GU J Sci 38(1): 146-157 (2025) DOI: 10.35378/gujs.1449089

Gazi University

Journal of Science

http://dergipark.gov.tr/gujs

Anti-Windup PID Control for Globe Valve Internal Disturbances: Design and Simulation Approach

Philip ADEWUYI[1, *], Lukman ANIMASHAUN[2]

[1]*Bells University of Technology, Department of Mechatronics Engineering, Ota, Nigeria*
[2]*Lagos State Universtity of Science and Technology, Department of Mechatronics Engineering, Ikorodu, Nigeria*

Highlights

- This paper focuses on the study of internal happenings in a globe valve.
- A proper control technique approach to efficiently deliver the output is presented.
- Globe valve's response to these disturbances are adequately presented for better analytical purpose.

Article Info

Received: 17 Mar 2024
Accepted: 16 Sep 2024

Keywords

Anti-windup
PID
Valve
SIMULINK
Breakaway

Abstract

Internal disturbances of a working globe valves come in three variants. The variants are the breakaway point, the stuck point, and the moving friction point. The breakaway point is the point where the fluid is just about to be free after being stuck for some period within the medium. This point comes with excessive friction and it is expected that the globe valve should be able to withstand this excessive friction. At stuck point, initial movement of fluid is practically stalled due to friction which should not be allowed to prolong to prevent damage of the globe valve. The moving friction point is the normal operational point friction of the globe valve when handling fluid movement. In practice, these disturbances transition from one point to another sequentially making them seem combined because of the fast rate at which they transition. In order to solve these problems, the natures of these disturbances are modeled mathematically and simulated using SIMULINK. Then, Anti-windup Proportional Integral Derivative controller (AW-PID) is introduced to control the operation of the globe valve to overcome the saturation effect associated with actuators which the conventional PID controller could not handle effectively. For a medium without the disturbances, AW-PID gives an overshoot of 1.40%, rise time of 0.015s for a unit step input function at 0.0042s settling time. For a fully working globe valve, an overshoot of 7.25% is obtained for a unit step input function with a rise time of 0.133s and a settling time of 0.536s. This work presents an improved technique to handle the internal disturbances of a working globe valve.

1. INTRODUCTION

The important objective of valve operation is to have a smooth and safe delivery of product. A particular valve used for this work is a globe valve which has been modeled from Newton's law and D'Alembert principle [1]. It has been established that internal disturbances encountered by a working valve are; breakaway point, stuck point, and moving friction. These disturbances have to be overcome without significantly affecting the magnitude of product delivery by the valve [2]. Leakage is a major problem encountered in the operation of valves. A means of early detection would go a long way to preserving the integrity of the operation of the valve [3]. As part of measures that have been proposed to monitor the internal operation of the valve is a non-intrusive acoustic monitoring technique. This technique uses dual-sensor. It has high leakage detection sensitivity. However, sampling frequency is still prevalent [4] .

Oscillation is another unwanted event in the operation of valve. This could affect the process flow and the path of feedback. Any system that experiences oscillation is liable to erratic control performance. It is important to detect oscillation sources and their paths of propagation. To combat the problem of oscillation, a latent variable technique has been used to handle common oscillations. The combination of both time-

*Corresponding author, e-mail: solaadewuyi@gmail.com

domain Granger causality and spectral Granger causality to provide an in-depth diagnosis has been proposed. This method still need more data analysis accuracy [5, 6].

In order to mitigate the internal disturbances of globe valve, it is pertinent to understand the complex nature of the fluid flow inside its medium whose characteristics are nonlinear with geometry that is complicated. This complexity could be studied with the use of numerical modeling. Therefore, flow characteristics and losses are as a result of orifice and flow ben in a globe valve could be modeled with the use of commercial CFD package STAR CCM+ with varying conditions [7]. Intrusive and non-intrusive methods have also been applied for fluid diagnostics and flow conditions monitoring in a control valve such as globe valve. Several loops of process control systems were studied and controlled using good control techniques. A multi-hole probe (MHP) with different probe lengths and heights has been used to obtain information on the local flow parameters for analysis on how the parameters affect the overall behaviour of the valve. Sensors, such as acoustic and vibration have been helpful for data extraction for subsequent analysis with the help of statistical parameters [8].

To further understand the type of flow at each valve opening, a multiphase flow simulation known as OLGA was used as a means of comparison with experimental results from two-phase flow-loop parameter obtained from downwardly inclined pipe and vertical riser [9]. An estimated transfer function of the resulting model was used to tune the PI controller's gain with a technique called the Internal Model Control (IMC). This allows for obtaining the PI gain using one tuning parameter. This goes a long way to mitigating severe slugging within the flow medium [10]. Vibration is another factor which could disrupt the smooth operation of globe valve. This is caused by rapid pump startup-shutdowns operation following pulsatile flows. Analysis is carried out based on the transient and steady-state response characteristics of acoustic and structural vibrations [11].

The choice of dynamic anti-windup proportional integral derivative control technique has been applied to linear systems with satisfactory performance of the system. The linear matrix inequalities was used to explicitly solve the anti-windup compensator gain [12]. Since saturation effect is typical of actuators operation, anti-windup proportional integral derivative controller has been used to reduce the effect of saturation in such systems with effective range of reset of integral term thereby preventing it from reaching the saturation [13]. In addition, augmented Lyapunov-Krasovskii functional has also been used to address the issues of time-delayed anti-windup problem. The resulting optimization problem is further solved with optimal performance indices [14].

SIMULINK has been effectively used to implement anti-windup proportional integral derivative control technique for various models which are prone to saturation effect [15]. In fact, both pneumatic and hydraulic systems are not left out as the technique, if well designed would address the issue of saturation. The range of input/output of the saturation curve is studied to so as to choose the control scheme suitable to guarantee improved system performance [16].

This study considers issue of saturation as a problem when a PID controller is used in conjunction with an actuator. Issue of a suitable controller to overcome the combined problems of moving friction, stuck point, and breakaway point is a problem that has to be solved. The AW-PID would be tuned using an improved Ziegler Nichol's tuning method [17]. Therefore, the technique presented to overcome this problem in this study presents a new approach to solving these problems in the area of globe valve fluid handling operations.

The rest of the paper is divided into; materials and methods, results and discussion and conclusion.

2. MATERIAL AND METHOD

This section would look into the development of models of a working globe valve, the three friction point conditions, AW-PID tuning approach, and Simulink representations of the models for simulation purpose.

2.1. Model of a Working Globe Valve

Globe valve was modeled in line with the force balance equation, F_M which is the inertia force due to mass of diaphragm and stem which are the moving parts of globe valve. According to Newton's second law of motion, the inertia force would be equal to the product of mass and acceleration according to Equation (1)

$$F_M = Ma(t). \tag{1}$$

In terms of velocity v(t), since acceleration is the rate of change of velocity, Equation (1) is written as Equation (2)

$$F_M = M\frac{dv(t)}{dt}. \tag{2}$$

In terms of displacement x(t), since velocity is the rate of change of distance with time, Equation (2) becomes:

$$F_M = M\frac{d^2x(t)}{dt^2}. \tag{3}$$

Equation (3) in terms of various forces associated with the valve is written as Equation (4)

$$M\frac{d^2x(t)}{dt^2} = F_a + F_r + F_f + F_p + F_i. \tag{4}$$

$F_a = Au$ is the applied force by the actuator where A is the diaphragm area and u is the globe valve input signal. $F_r = -kx$ is the spring force where k is the spring constant, $F_p = -\propto \Delta P$ is the force due to fluid pressure drop where $\propto$ is the plug unbalance area and ΔP is the fluid pressure drop across the valve, F_i is the extra force required to force the valve to be into the seat and F_f is the friction force. The friction model as used by [18] is represented by Equation (5). The first line represents the expression when globe valve is moving and comprises of a velocity-independent term F_c known as Coulomb friction and viscous friction term vF_v that depends linearly upon velocity. Both acts oppose the velocity as shown by the negative signs

$$F_f = \begin{cases} -F_c sgn(v) - vFv, \ if \ v \neq 0 \\ -(F_a + F_r), \ if \ v = 0 \ and \ |F_a + F_r| \leq F_s \\ -F_s sgn(F_a + F_r), \ if \ v = 0 \ and \ |F_a + F_r| > F_s. \end{cases} \tag{5}$$

For a moving globe valve friction, Equation (6) holds

$$M\frac{d^2x(t)}{dt^2} = Au - kx - F_c sgn(v) - vF. \tag{6}$$

By applying Laplace transform and solving for X, Equation (6) turns to Equation (7)

$$X(s) = \frac{ASU(s)}{MS^3 + F_v S^2 + kS} - \frac{F_c sgn(v)}{MS^3 + F_v S^2 + kS}. \tag{7}$$

For a stuck globe valve friction, Equation (8) holds

$$M\frac{d^2x(t)}{dt^2} = Au - kx - (F_a + F_r). \tag{8}$$

By applying Laplace transform and solving for X, Equation (8) turns to Equation (9)

$$X(s) = \frac{ASU(s)}{MS^3 + kS} - \frac{(F_a + F_r)}{MS^3 + kS}. \tag{9}$$

For a globe valve breakaway, Equation (10) holds:

$$M\frac{d^2x(t)}{dt^2} = Au - kx - F_s sgn(F_a + F_r). \tag{10}$$

By applying Laplace transform and solving for X, Equation (10) turns to Equation (11)

$$X(s) = \frac{ASU(s)}{MS^3+kS} - \frac{F_s sgn(F_a+F_r)}{MS^3+kS}. \tag{11}$$

For the anti-windup PID, the conventional PID controller, $G_1(s)$ is given as Equation (12)

$$G_1(s) = k_p + \frac{k_i}{S} + k_d S, \tag{12}$$

where k_p is the proportional gain. k_i is the integral gain. k_d is the derivative gain.

The anti-windup technique was developed in relation to the limiter as presented in Equation (13)

$$U_o = \begin{cases} U_{ma}, & if\ U \geq U_{ma} \\ U, & if\ U_{mi} \leq U \leq U_{ma} \\ U_{mi}, & if\ U \leq U_{mi}, \end{cases} \tag{13}$$

where U_o is the limiter's output, U_{ma} is the maximum output value of the limiter, and U_{mi} is the minimum output value of the limiter. also, U is the input value of the limiter.

Considering Equation (12), integral term could be written in form of integral time constant, tracking time, and input value of the limiter as presented in Equation (14). Therefore,

$$\frac{K_i}{S} \equiv e_i = \frac{K_p}{T_i}e + \frac{1}{T_t}(U - U'), \tag{14}$$

where K_p is the proportional gain, T_i is the integral time constant, T_t is the tracking time constant, U' is the process input, and U is the controller output, and e_i is the integral term.

To reset the integral term, T_t is adjusted using Equation (15)

$$T_t = \sqrt{}(T_i \times T_d), \tag{15}$$

where T_d is the derivative time.

Laplace transforms of Equation (14), substitutes in Equation (12) results in Equation (16)

$$G_1(S) = \frac{K_pT_iT_t + K_pT_te + T_i(U - U') + K_dT_iT_t}{T_iT_t}. \tag{16}$$

Separating Equation (16) into like terms results in Equation (17)

$$G_1(S) = \frac{[K_pT_i + E(S) + K_dT_i]}{T_i} + \frac{U(S) - U'(S)}{T_iT_t}. \tag{17}$$

From Equation (17),

$$G_1(S) = K_pK_d + \frac{E(S)}{T_i} + \frac{U(S) - U'(S)}{T_iT_t}, \tag{18}$$

Since $E(S) \approx U(S) - U'(S)$.

Equation (18) could be written as Equation (19), given as

$$G_1(S) = K_pK_d + \frac{U(S) - U'(S)}{T_i} + \frac{U(S) - U'(S)}{T_iT_t}. \tag{19}$$

Letting

$'a' = K_p K_d$, $'b' = \frac{U(S)-U'(S)}{T_i}$, and $'c' = \frac{U(S)-U'(S)}{T_i T_t}$.

By comparing $'b'$ and $'c'$, the saturation effect is reduced by T_t factor in $'c'$, thereby making the actuator avoid reaching the state of full saturation.

2.2. Tuning of Anti-windup PID

The anti-windup PID controllers were tuned as shown in Figure 1 which has a display of its block response and the tuned response respectively. Table 1 consist of the tuning parameters starting with the initial value of proportional constant of 1, integral value of 1, and derivative value of 0. The final tuned parameters for proportional, integral, and derivative values are as contained in Table 1.

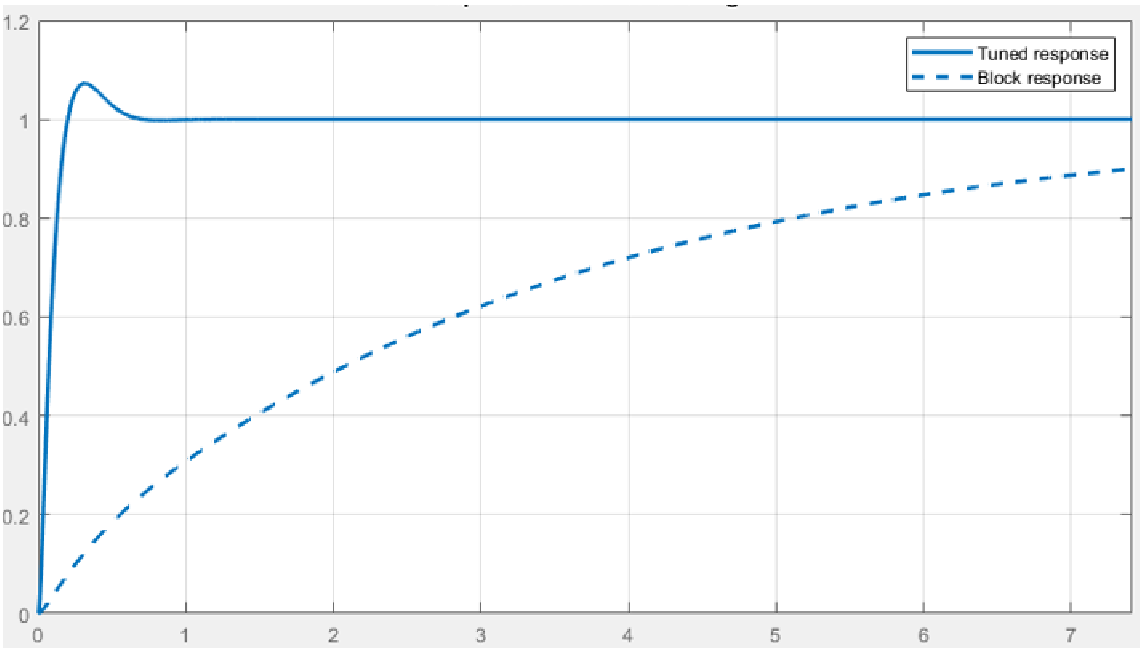

Figure 1. *Anti-windup controllers' tuned response*

Table 1. *PID tuned parameter results*

	Tuned	Block
P	92.67	1
I	858.8311	1
D	0.50808	0

2.3. Application of Anti-windup PID Controller to a Working Globe Valve

For practical globe valve operations, three operational conditions are experienced such as; breaking point, stuck point, and moving friction point. Breaking point is the point at which the globe valve is just about to run freely. Stuck point is the point where globe valve is stiff and demands high pressure for its release. The moving friction point is the state of normal operation of the globe valve as it handles the flow of fluid. These points are considered separately using both clamping and back-calculation anti-windup schemes for thorough analysis of the globe valve model. Figure 2 is the arrangement of anti-windup PID back-calculation model in Simulink. This was used to observe the performance of the globe valve with respect to time and corresponding displacement.

Figure 3 is the arrangement of the clamping anti-windup PID model in Simulink. Figure 4 shows the corresponding breakaway point model in Simulink. Figure 5 is the stuck point model in Simulink. Figure 6 is the arrangement of the moving friction point model. Back-calculation and clamping anti-windup techniques were applied to breaking point, stuck point, and moving friction point models respectively.

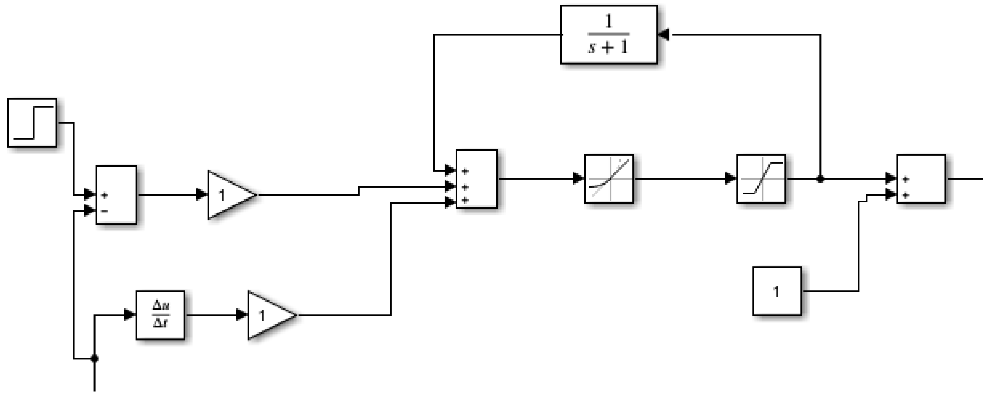

Figure 2. *Back-calculation Anti-windup PID model in Simulink*

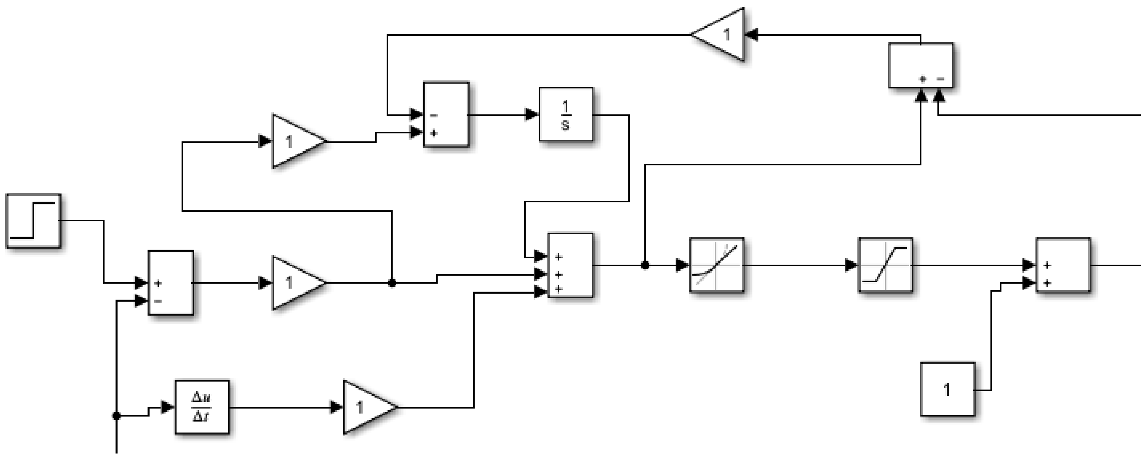

Figure 3. *Clamping Anti-windup PID model in Simulink*

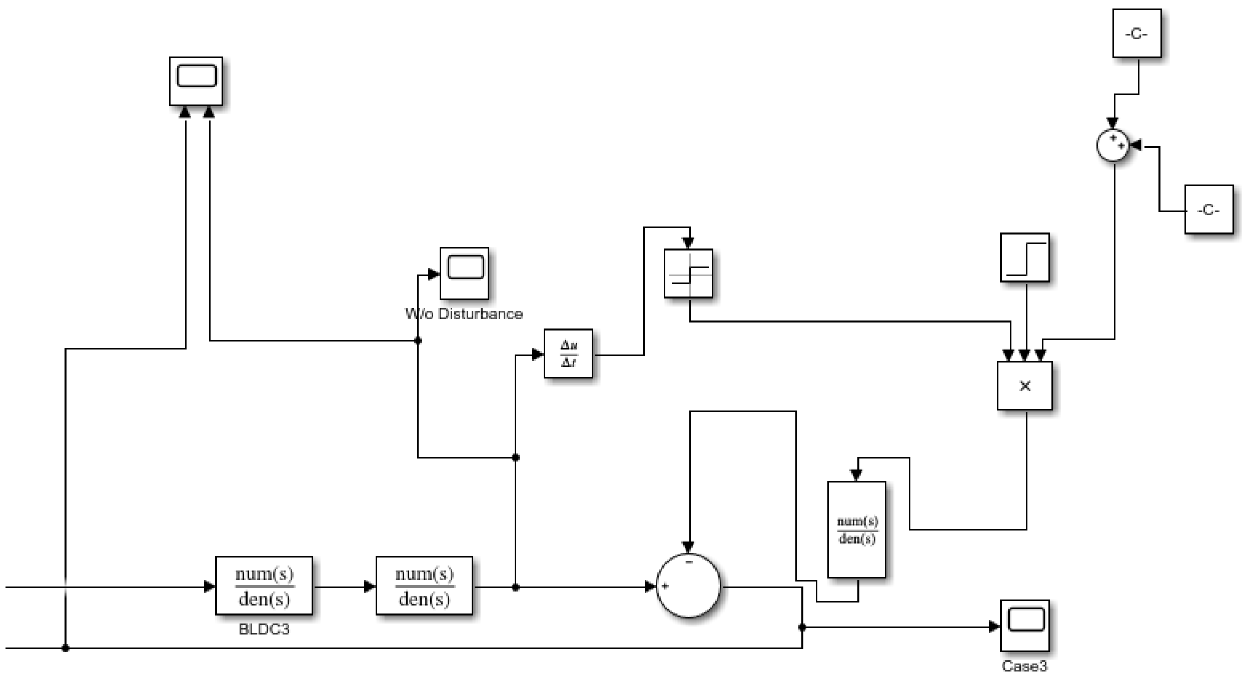

Figure 4. *Simulink representation of breakaway point*

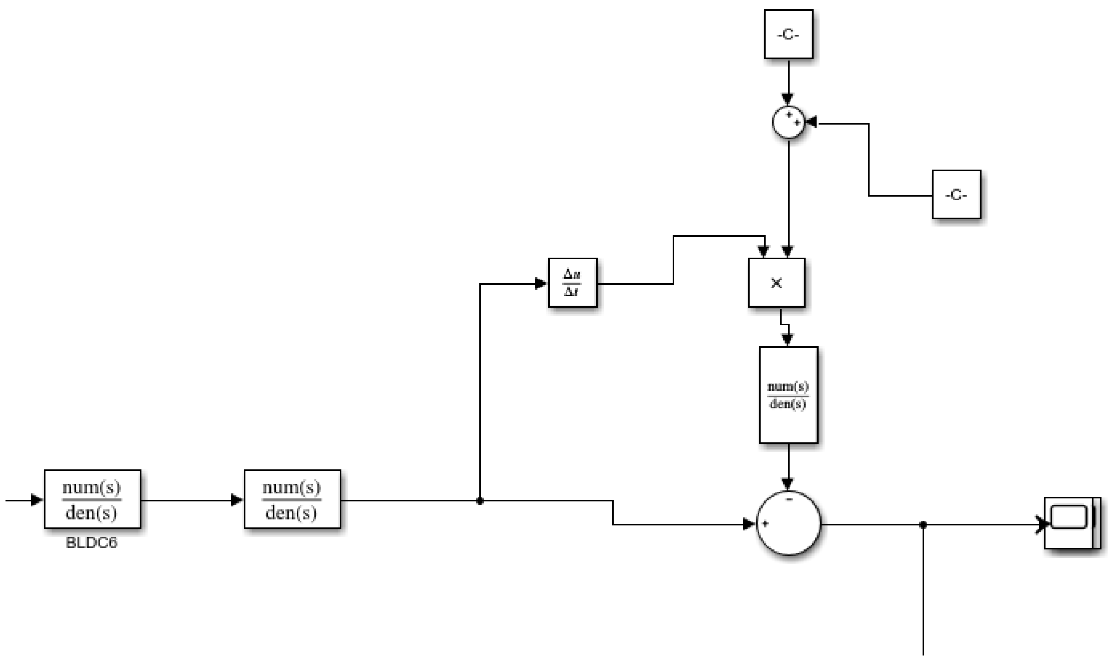

Figure 5. *Simulink representation of stuck point model*

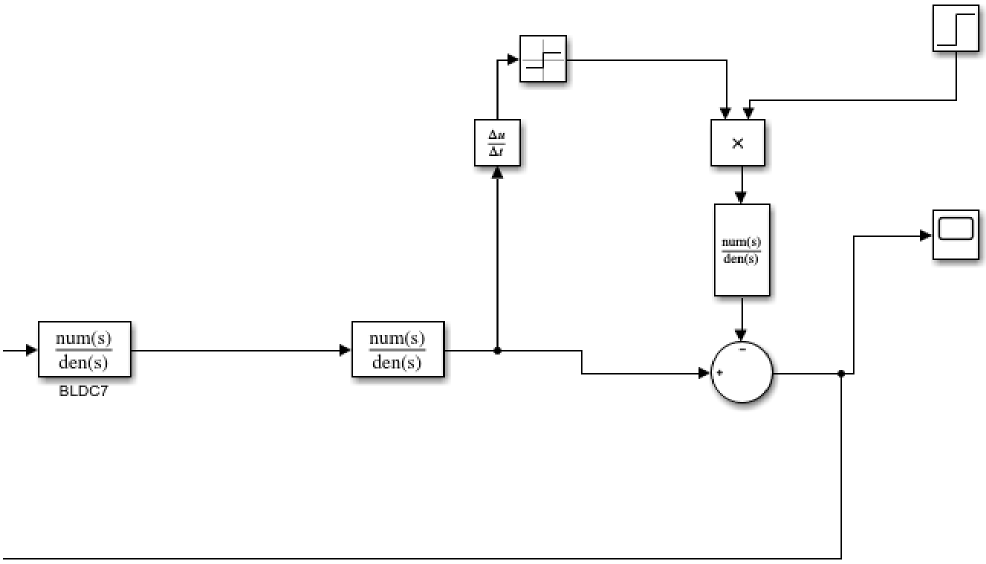

Figure 6. *Simulink representation of moving friction point model*

3. THE RESEARCH FINDINGS AND DISCUSSION

3.1. Globe Valve's Response to Changing Conditions

There are three conditions that globe valve experiences during operations. These conditions are:
(i) when the globe valve is at moving friction condition;
(ii) when the globe valve is at stuck point;
(iii) when the globe valve is at breakaway point.
These conditions were simulated and alongside the valve positions at each condition.

3.2. Moving Friction Condition

At moving friction point, the globe valve is at its normal functioning stage while handling fluid. Figure 7 shows that globe valve experiences initial oscillations due to the friction generated with the arrival of fluid as compared to when it is free of fluid product. This initial oscillation signal settles out after 18s to a normal operational characteristic of the globe valve as contained in Figure 7.

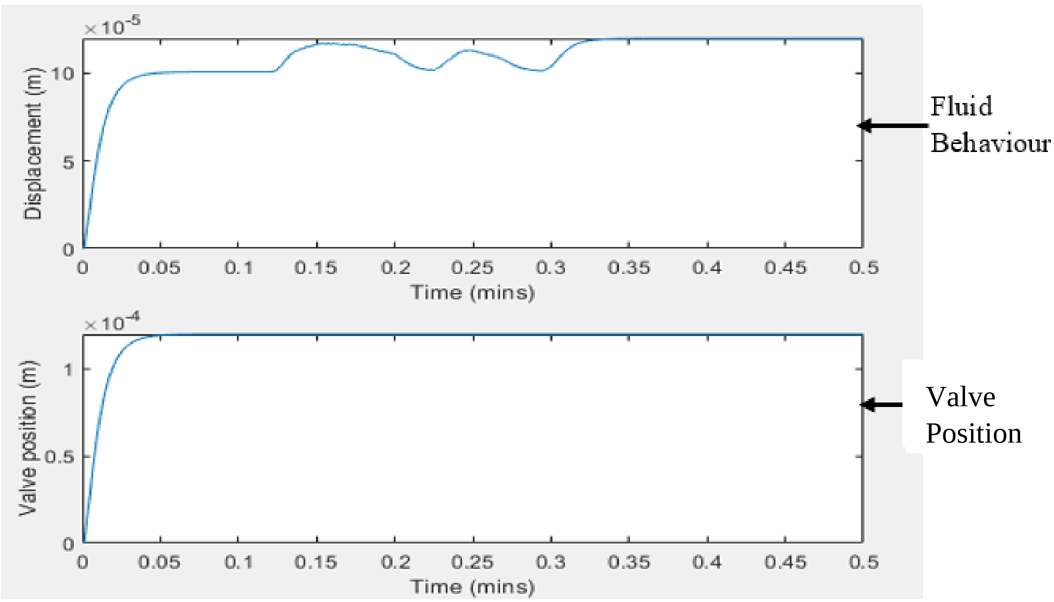

Figure 7*. Response of valve at moving friction point*

3.3. Stuck Point Condition

At stuck point condition, an initial stoppage of movement is experienced by the globe valve. Figure 8 shows the stuck point as the globe valve overcomes this initial obstruction to return to its free operational state. At stuck condition, more torque is required to overcome this initial friction before a smooth operational state is resumed. This stuck point condition last for 3 seconds and might cause damage to the globe valve if it extends beyond this tolerant point.

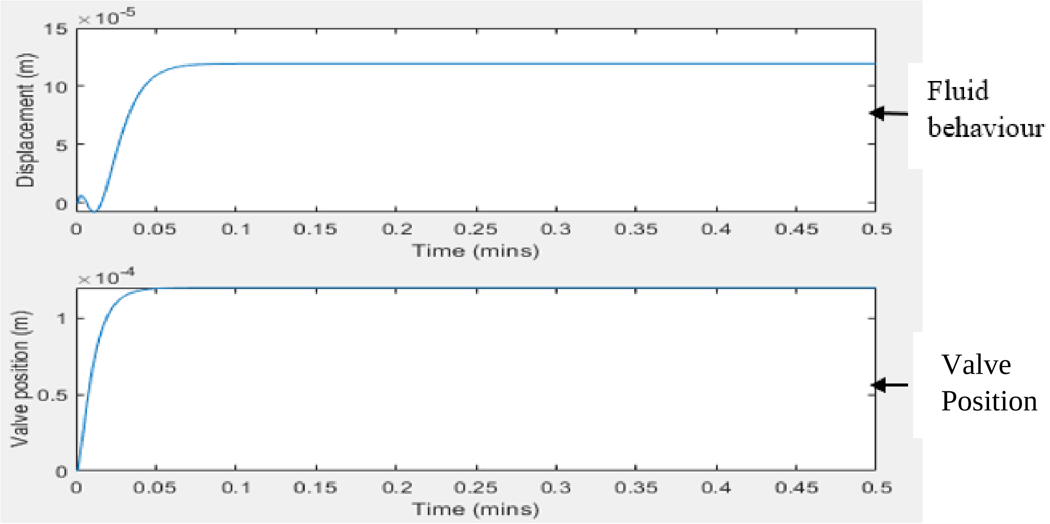

Figure 8. *Response of valve at stuck point*

3.4. Breakaway Point Condition

At breakaway point condition, oscillation is more pronounced as it involves so much friction. This point is critical as it determines the ruggedness of the built globe valve. The globe valve with the help of the anti-windup controller techniques deployed was able to overcome this friction at 21s and return to normal operational state as desired. Once the globe valve breaks away, free flow operation is resumed and all internal noise generated by the condition is brought to a near zero value as displayed in Figure 9.

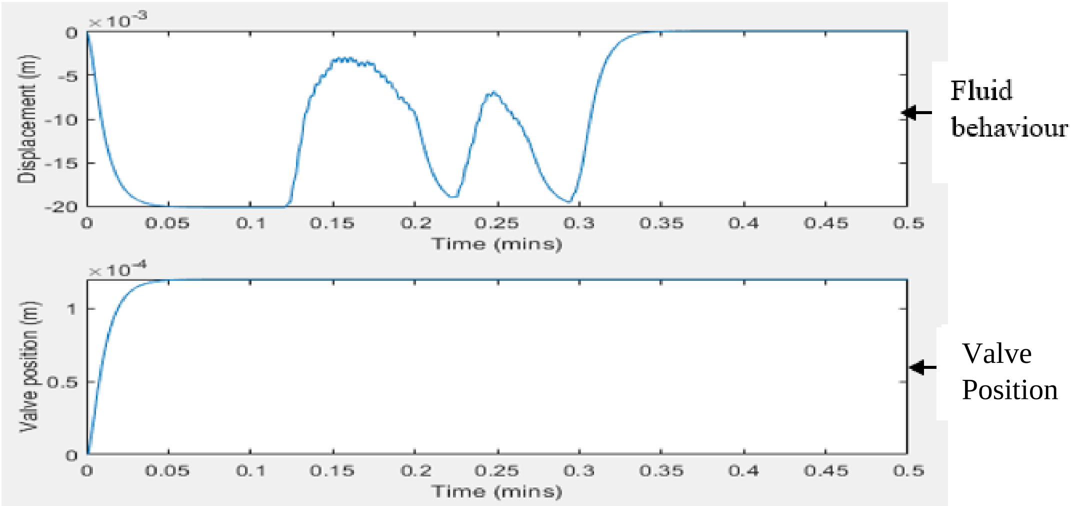

Figure 9. *Response of valve at breakaway point*

4. RESULTS

Having investigated the internal disturbances affecting the effective operation of globe valve when handling fluid, it has become important to ensure a smooth product delivery and extension of the life span of the globe valve system. Application of an anti-windup proportional integral derivative controller (AW-PID) ensures that stability of globe valve was achieved quicker and saturation effect due to integral term was eliminated. This further gives credence to the essence of having a suitable model with parameters selected to give optimal performance of the system that matches the overall goal of any controller as highlighted in Figure 10.

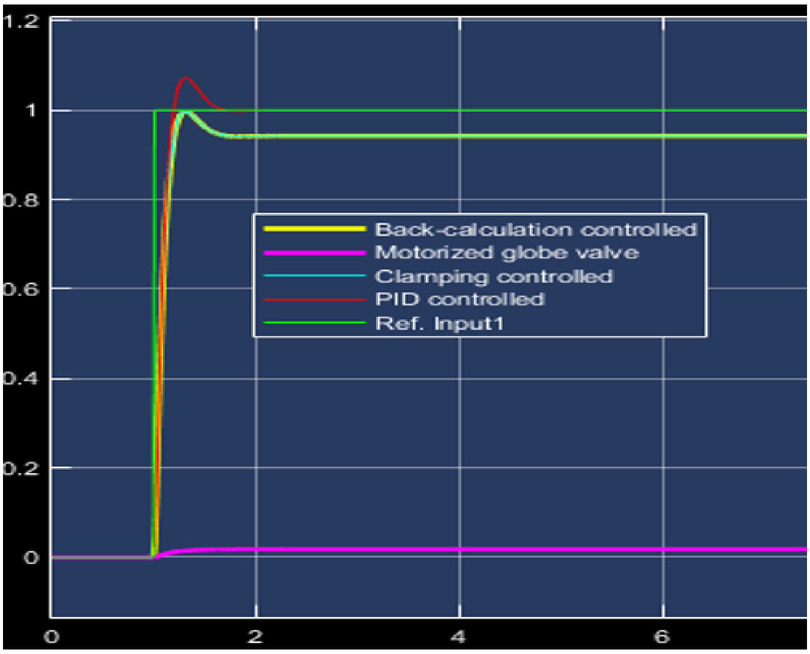

***Figure 10**. Performance results of AW-PID techniques*

Table 2 contains the comparison of AW-PID, Back-calculation and Clamping techniques performances at a glance. It should be noted that the responses of Back-calculation and Clamping techniques were before tuning.

***Table 2.** AW-PID, Back-calculation and Clamping techniques responses*

	AW-PID	Back-calculation	Clamping
Rise time	0.133s	7.16s	11.9s
Settling time	0.536s	21.8s	21.2s
Overshoot	7.27%	0%	0%

4.1. AW-PID Technique Response

The AW-PID response to the disturbance after tuning is as displayed in Figure 11. Typical of AW-PID operations, the response shows oscillations that had to settle in less than 3 seconds. Figure 11 displays AW-PID response when disturbance was not introduced to the system and response when disturbance had been introduced into the system. The performance shows that saturation was present justifying the application of anti-windup techniques to its control operations.

The performance of AW-PID indicates that for every controller, it is expected that the controller should be able to bring about stability of the system irrespective of the initial instability due to various internal and external disturbances. This is the hallmark of a good controller meeting design objectives in terms of performance. AW-PID in its present format has therefore satisfied the design objectives of this work.

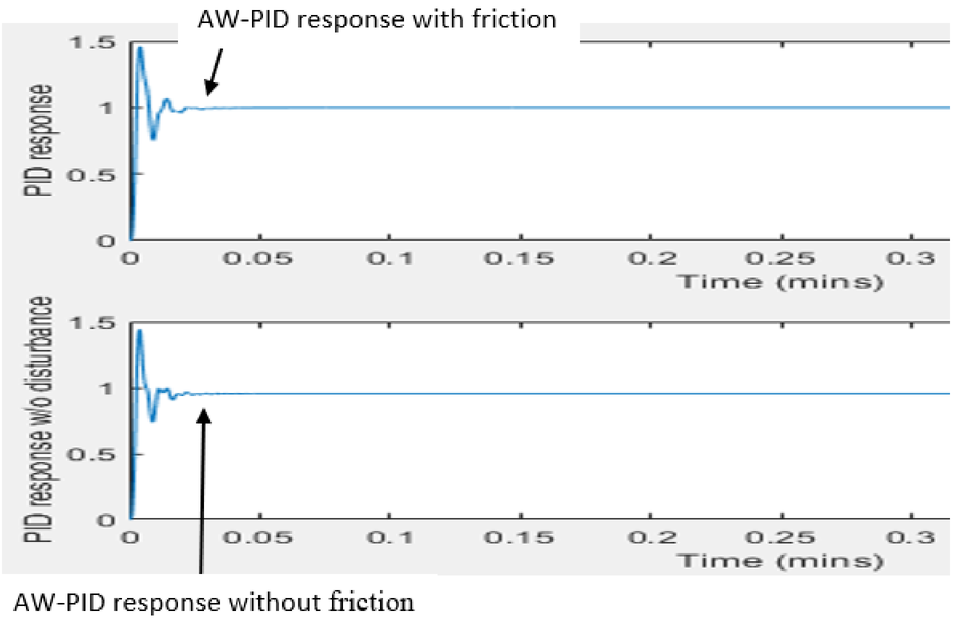

***Figure 11**. AW-PID response*

5. CONCLUSION

This work has provided valuable insights into the practical behaviour of a globe valve system during fluid handling condition. The three prevalent conditions present themselves as frictions in different forms and magnitudes that were well handled thereby preventing system damage. These friction conditions are non-linear in nature and were successfully modelled mathematically and simulated. AW-PID controller was introduced as the conventional PID controller could not satisfactorily contain the saturation effect of the globe valve. Back-calculation and clamping AW-PID techniques were applied with an average rise time of 0.133s, overshoot of 7.27%, and settling time of 0.536s to bring about stability of the system.This clearly shows that either back-calculation and clamping AW-PID techniques could be used independent of each other when properly tuned for the purpose of controlling globe valve system handling the flow fluid within an enclosed medium. Future works would seek to implement these findings in differennt climatic conditions in order to obtain results that could be generalized for further operational improvements.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

REFERENCES

[1] Cruz, P., Batista, P., and Sanyal, A., “Attitude observers for three-vehicle heterogeneous formations based on the Lagrange-d’Alembert principle”, 2021 European Control Conference (ECC), Delft, Netherlands, 2317-2322, (2021).

[2] Wang, H., Zhu, Z., Xu, H., and Li, J., “Effects of throttling structures on cavitation flow and circumferential uniformity in a control valve”, Engineering Failure Analysis, 134, 106025, (2022).

[3] Gangadiya, A. J., George, P. M., Pandya, V. A., and Ayar, M. S., “Optimization of turning parameters to control concentricity of globe plug check valve”, AIP Conference Proceedings, 2317, 050012, (2021).

[4] Lin, W., Wu, S., Shi, Y., and Wang, F., “Research on non-intrusive acoustic monitoring for valve internal leakage”, in 2017 29th Chinese Control and Decision Conference (CCDC), 7796–7801, (2017).

[5] Yuan, T., and Qin, S. J., “Root cause diagnosis of plant-wide oscillations using Granger causality”, Journal of Process Control, 24: 450–459, (2014).

[6] Sotoodeh, K., “A Review and Analysis of Industrial Valve Material Failures Due to Corrosion and Proposals for Prevention Measures Based on Industrial Experiences in the Offshore Sector of the Oil and Gas Industry”, Journal of Failure Analysis and Prevention, 21: 261–267, (2021).

[7] Tewari, K., Dewan, A., Narayanan, V., “Computational Fluid Analysis of Flow Losses in Globe Valves”, In: Bhattacharyya, S., Chattopadhyay, H. (eds) Fluid Mechanics and Fluid Power. Lecture Notes in Mechanical Engineering, Springer, Singapore, 1, 19-23, (2023).

[8] Airede, Y. O., “Intrusive and Non-intrusive Methods for Fluid Diagnostics and Flow Condition Monitoring in a Control valve”, (University of Huddersfield, (2019).

[9] Park, K. H., Sohn, Y. H., Jang, W., and Seo, Y., “Experimental Investigation of Severe Slugging in Vertical Riser and Its Mitigation with Inlet Choke control”, in (OnePetro, 2019).

[10] Park, K.-H., Kim, T.-W., Kim, Y.-J., Lee, N., and Seo, Y., “Experimental investigation of model-based IMC control of severe slugging”, Journal of Petroleum Science and Engineering, 204, 108732, (2021).

[11] Ahmed, F., Eames, I., Azarbadegan, A., and Moeendarbary, E., “Acoustics and vibrations in a complex piping network with pump startup–shutdown transients”, International Journal of Mechanical Sciences, 227, 107357, (2022).

[12] Chen, Y., Ma, K., and Dong, R., “Dynamic anti-windup design for linear systems with time-varying state delay and input saturations”, International Journal of Systems Science, 53: 2165–2179, (2022).

[13] Lopes, A. N. D., Leite, V. J. S., Silva, L. F. P., Guelton, K., “Anti-windup TS Fuzzy PI-like Control for Discrete-Time Nonlinear Systems with Saturated Actuators”, Journal of Intelligent & Fuzzy Systems, 22(1): 46-61, (2020).

[14] Chen, Y., Fu, Z., Fei, S., and Song, S., “Delayed anti-windup strategy for input-delay systems with actuator saturations”, Journal of the Franklin Institute, 357: 4680–4696, (2020).

[15] Alifdhyatra, A. F., Sunarya, B. A. Y., Hidayat, E. M. I., Anshori, I., and Hadi, Y. W., “Development of Pneumatic Networks Soft Robot with Anti-Windup PID Control”, in 2022 IEEE 13th Control and System Graduate Research Colloquium (ICSGRC), 25–30, (2022).

[16] Kavyashree, B.G., Patil, S., Rao, V. S., “Observer-based anti-windup robust PID controller for performance enhancement of damped outrigger structure”, Innovative Infrastructure Solutions, 7(205), (2022).

[17] Widagdo, R. S., Hariadi, B., and Setyadjit, K., “Modelling and Analysis of Ziegler-Nichols and Chien-Hrones-Reswick Tuning PID on DC Motor Speed Control”, Jurnal Teknologi Elektro, 14: 23-27, (2023).

[18] Choudhury, M. A. A. S., Thornhill, N. F., and Shah, S. L., “Modelling valve stiction”, Control Engineering Practice, 13: 641–658, (2005).