

Improving Manufacturing Sustainability Through Statistical Analysis of Sinusoidal Valve Stiction

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Received: 2 Jun. 2025, Revised: 2 Sep. 2025, Accepted: 1 Oct. 2025.

Published online: 1 Nov. 2025.

Abstract: Modern manufacturing enterprises face many challenges that have to be overcome to keep the operation sustainable and effective. Among the key issues is the stiction of control valves that may cause inefficiency in process operations, increased energy consumption, and disturbed production stability. This article is devoted to exploring a sinusoidal compensation method in order to address stiction challenges. The proposed methodology will contribute to enhancing industrial process sustainability by reducing oscillatory behavior in manufacturing systems, hence ensuring smooth operations with minimal environmental impact.

Keywords: Sustainable manufacturing; Valve stiction; Process optimization; Energy efficiency; Sinusoidal compensation; Production stability.

1 Introduction

Control systems in manufacturing, especially in maintaining product quality and operational efficiency, have a vital role. The nonlinearities in valve movement cause stiction, a condition that has an adverse effect on process sustainability by wasting more resources and reducing profitability, mainly due to unneeded control movements and more usage of power and possibly material. By addressing stiction, efficiency will be improved, and sustainable manufacturing is enhanced with better use of energy and materials. The present study investigates a sinusoidal compensation method and presents it as a sustainable solution for the industrial manufacturing enterprise control valve stiction problem.

Valve stiction usually is modeled as a sum of static and dynamic frictions. The most usually applied LuGre friction model and other empirical models mathematically represent the stiction. A very simplified representation of the behavior of valve stiction may be described as:

$$f(t) = F_s + \mu \cdot v(t), \text{ if } |x(t)| \leq x_{stick} \quad (1)$$

$$f(t) = F_c + \mu \cdot v(t), \text{ if } |x(t)| \geq x_{stick} \quad (2)$$

where:

- $f(t)$ is the friction force at time t .
- F_s is the static friction (force required to overcome stiction).
- F_c is the dynamic (kinetic) friction.
- $v(t)$ is the velocity of the valve stem.
- $x(t)$ is the displacement of the valve stem.
- x_{stick} is the threshold displacement for stiction.

This equation reflects friction force dependence on either sticking or moving of a valve, where friction is larger under static conditions. Stiction is the resistance to the start of motion, usually measured as the difference between the driving values required to overcome the static friction upscale and downscale.

Indeed, from a study of real process data, it is observed that the phase-plane portrait of a valve input vs. output response for a stick valve can be characterized, as shown in figure 1. It comprises a deadband, stick band, slip jump, and a moving phase.

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When the valve comes to a rest or changes direction to 'A point,' the valve sticks. Once the controller output overcomes the dead band 'AB' plus the stick bank 'BC' of the valve, the valve jumps to a new position, 'point D', and continues to move. The deadband and stickband represent the behavior of the valve when it is not moving even though the input to the valve is changing. The slip jump represents the sudden release of potential energy stored in the actual chamber as kinetic energy due to high static friction as the valve starts to move. Once the valve moves, it continues to move until it sticks again at point E.

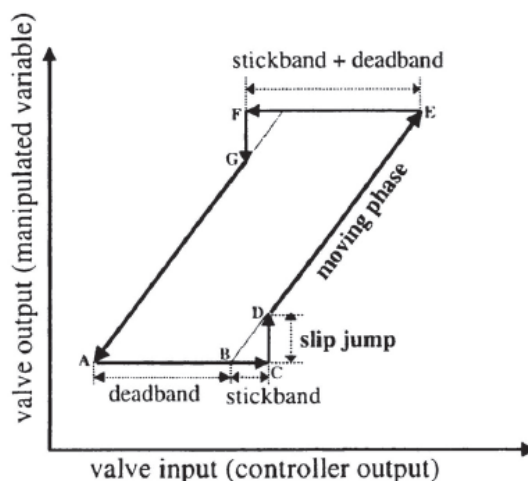


Fig. 1: Typical input-output characteristic of a sticky valve [1]

There are two loops simulated under closed loop, which are the concentration loop and a level loop. The concentration loop has slow dynamics with large dead time, while that for the level loop only has an integrator. The transfer function obtained from Horch and Isaksson [2], 1998, along with the stiction model, was used for its simulation. Since it is known that the presence of pure deadband or backlash does not form a limit cycle, but, in contrast, it only adds dead time to the process, while that for deadband with an integrator produces a limit cycle. The plot of valve position (mv) against controller output (op) is presented, showing the elliptical loops with the sharp turnaround points. Level loop was investigated using only an integrator for the typical behavior of the process in the presence of valve stiction. From the simulation, it follows that the presence of a pure dead band is enough to cause oscillations. A pure dead band, hence, can create limit cycles by adding an integrator in the process, or the cycle otherwise will decay to zero. The same kind of PV-OP plots of elliptical loops with sharp turnarounds is obtained from simulation [1].

2 Literature Review

Stiction in control systems has been a subject of research due to its pervasive impact on manufacturing enterprises. Previous studies have looked into various methods, including model-based and model-free compensation techniques [1], [3], [4], [5], [6], [7], [8], [9], [10]. However, most of these methods tend to increase the wear and energy consumption of the system. The sinusoidal compensation method proposed in this paper extends previous works by introducing a sustainable approach with smoother valve movements and less variation. Some of the most relevant findings from previous works are:

1. Pulse Compensation: Effective in eliminating oscillations but causes rapid wear on valves, hence not sustainable for long.
2. Tuning Proportional-Integral (PI) Controllers: Mitigates stiction but at the cost of increased steady-state errors.
3. Sinusoidal Compensation: Demonstrated to offer optimal results in reducing oscillatory behaviors with minimal energy use while maintaining system robustness.

In addition, sustainable practice integration within manufacturing enterprises has become a high priority for addressing operating-related inefficiencies. Of the various losses that reduce efficiency, stiction of control valves results in oscillatory behavior in industrial systems, which causes a lot of resource wastage in terms of energy and material. Hence, efficient stiction compensation methods contribute significantly to sustainable manufacturing and enterprise optimization. It is a review that reflects on prevailing methods and their limitations while introducing sinusoidal compensation as an effective alternative. A group of authors observed that stiction affects the control loop performance as well as accelerates wear and tear of valves, hence causing the reduction in the lifecycle of the valve [2], [11], [12], [13], [14], [15], [16].

Different approaches have been advanced to minimize stiction in the control valve with various levels of success. One such approach, known as pulse compensation, implements small periodic pulses to surmount static friction. This approach, however, is found to dampen oscillations but again was faced by criticism with regard to the aggressiveness of the stem movements resulting in rapid valve wear. It is also a computationally expensive process since it involves the tuning of several pulse parameters [6], [17].

PI/PID controller tuning was prevalent among the approaches used to compensate for stiction; under this technique, an appropriate tuning of the controller gain and reset time results in reducing the amplitude of oscillations. [18]. However, studies have shown that PI/PID tuning may introduce steady-state errors and increase the frequency of limit cycles, compromising system efficiency [5], [13].

Model-free methods have attracted interest due to their dynamic adaptability without a precise model of the control system. Examples include constant reinforcement (CR) methods, which inject a compensating signal into the valve to maintain the movement [18]. Besides, most of them cannot effectively handle severe stiction cases.

Model predictive control (MPC) design was used, which involves both a control and optimization approach for valve stiction. The MPC was used in integration with the conventional PI/PID method [19], [20], [21].

Optimization methods had been implemented seeking an optimum set of parameters for compensation using mathematical models. Canudas de Wit et al. (1995) worked on developing an optimization framework based on stiction severity estimation. While this method attains precision, it is also restricted by computational inefficiencies and the possibility of local minima, especially in complex industrial systems, as in [22].

The sinusoidal compensation method addresses the limitations of existing techniques by introducing a non-aggressive compensating signal that reduces variability and energy use. According to [1], [4], [23], this method minimizes valve wear by employing sinusoidal waves characterized by fundamental frequencies, eliminating the harmonics that cause sudden valve movements in pulse-based methods. Furthermore, the sinusoidal approach has exhibited superior performance in reducing ISE values at various stiction severities and, thus, can be a robust choice for sustainable manufacturing operations.

Wu et al. (2020) discussed the dynamic nature of stiction and its influence on process stability, underlining the need for advanced compensation methods in sustainable manufacturing conditions [24].

Several advanced methods have been developed recently to address stiction. Neural network models had been used in combination with other model-based techniques in the quantification and compensation of the valve stiction. Recent works apply machine learning for predictive stiction management, such as in [25], [26], [27], [28]. This involved learning vector quantization or convolutional neural networks. The benefit of the various neural network models is that they involve a group of various control loops of industrial data that involve linear and non-linear loops, as well as noise involvement within the signals.

Di Capaci et al. presented a cloud-based monitoring approach that integrates data analytics into predictive algorithms for the mitigation of stiction. This helped in enhancing sustainability by the reduction of process disruptions [12], [25]. Wu et al. (2020) performed a critical review of dynamic modeling approaches for stiction, which helped in reducing oscillations and consequently enhances energy efficiency [24]. These models allow very accurate predictions and real-time adjustments that support sustainable operations. Sinusoidal compensation remains one of the robust approaches to reducing valve wear and oscillatory behavior. Recent studies, such as [29], have validated its efficacy in the improvement of process control stability while conserving energy and material. Stiction detection has also been introduced with integrated systems for condition monitoring and control optimization. For instance, in the work of [30], a technological demonstrator for cloud-based performance monitoring is presented, allowing real-time diagnostics while answering sustainability goals. Principal component analysis, linear discriminant analysis, and a one-class support vector machine were trained to detect stiction using time series features as input [31].

Among them, machine learning-based techniques have excellent adaptability and predictive performance but involve huge computational resources. Dynamic modeling would imply a too complex implementation in an industrial manufacturing scenario. Sinusoidal compensation remains a very simple and effective solution to be applied in a variety of manufacturing situations. Integrated systems allow thorough monitoring but depend on the availability of adequate infrastructure.

Stiction detection techniques using a support vector machine with generalized statistical variables, convolutional neural networks, and phase space reconstruction methods were implemented to detect stiction, which further can be used as information for valve compensation [32], [33], [34].

The contribution of reviewed methods refers to the scope of operational inefficiency, as well as to wider sustainability goals due to optimized resource use and minimized emissions. In [26], predictive analytics highlighted their potential for waste

minimization, while other authors underlined the dynamic model in terms of energy saving [16], [35]. This section summarizes different methods applied for stiction compensation in control valves [4], [12], [24], [30].

2.1 Summary Table of Compensation Methods

Below is the comprehensive summary table, including the equations commonly used for each stiction compensation method:

Table 1: Summary table of Valve Stiction Compensation Methods

Method	Principle	Equation	Advantages	Limitations
Pulse-Based	High-frequency pulses	$u(t) = u_{base} + A_p \cdot \sin(\omega_p t)$	Effective for extreme stiction	Rapid wear and high energy cost
Sinusoidal Compensation	Smooth sinusoidal inputs	$u(t) = u_{control} + A_s \cdot \sin(\omega_s t)$	Energy-efficient, reduces wear	Requires tuning
PID Tuning	Adjusting controller gains	$u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt}$	Simple to implement	Risk of steady-state errors
Model-Based Compensation	Friction modeling	$f(t) = F_s + \mu \cdot v(t), \text{ if } x(t) \leq x_{stick}$ $f(t) = F_c + \mu \cdot v(t), \text{ if } x(t) \geq x_{stick}$	x(t)	Computational complexity
Machine Learning	Predictive algorithms	$u(t) = f_{ML}(x_t, v_t, \dots)$	Robust and adaptive	High computational demand
Constant Reinforcement	Small constant input bias	$u(t) = u_{control} + B$	Simple and cost-effective	Higher energy usage
Optimization-Based	Algorithmic input optimization	Maximize the objective function by minimizing the error.	u(t)	Computationally intensive

For the pulse method, $u(t)$ is the control input signal, A_p is the amplitude of the pulse signal, and ω_p is the frequency of the pulse. For the sinusoidal compensation, $u_{control}$ is the original control input signal, A_s is the amplitude of the sinusoidal signal, and ω_s is the frequency of the sinusoidal signal.

For the PID tuning, $e(t)$ is the error signal, and K_p , K_i , and K_d are the proportional, integral, and derivative gains, respectively. For the model-based compensation, $f(t)$ is the friction force. F_s : Static friction, F_c : Dynamic friction, $x(t)$: Valve stem displacement.

For the machine learning-based compensation, $u(t)$ is predicted using trained models f_{ML} , where inputs include historical data such as valve position (x_t) and velocity (v_t). For the constant reinforcement, B : Constant bias is added to the control signal to prevent static conditions.

2.2 Causes and Characteristics of Valve Stiction

Valve stiction is caused by static friction that prevents the valve from responding promptly to actuator signals, leading to oscillatory behavior and inefficiencies. Valve stiction results in uneven responses to control signals, particularly under high-pressure conditions, which disrupts process stability and increases energy demands [11], [18], [30], [36].

2.3 Impacts on Energy Consumption

The energy implications of valve stiction are multifaceted, including increased actuator workload, prolonged stabilization periods, and process inefficiencies. Stiction leads to excessive actuator movements, which, in turn, cause significant energy losses during frequent corrections. Models are implemented to analyze stiction-induced energy consumption, demonstrating that systems with unaddressed stiction used up to 30% more energy compared to compensated systems [16], [35], [36].

2.4 Detection and Diagnosis Techniques

Early detection of stiction is essential to reduce energy consumption and maintain the reliability of the system. Preprocessing techniques for early stiction detection using AI were proposed at industrial setups with improved diagnostic accuracy [37].

A correlation between stiction and control valve lifecycle prediction was established while highlighting the evaluation of detection algorithms in minimizing maintenance and energy costs [38]. Many approaches for stiction detection and quantification were proposed, noting its strong correlation with valve wear and process disruptions [8], [21], [27], [32], [39].

2.5 Compensation and Mitigation Strategies

There are several compensation techniques that address energy losses due to valve stiction. Di Capaci and Scali (2016) investigated system identification methodologies for quantifying stiction and showed a significant contribution of adaptive compliance in reducing energy waste [25]. Garrido et al. (2023) explored cost-effective compensation strategies for electric valves, demonstrating significant energy savings with optimized valve actuation paths and diminished oscillations [35].

2.6 Impacts on Maintenance and Operational Costs

Stiction causes not just energy waste but also increases wear and maintenance requirements on the valve. The oscillations caused by stiction increase valve movement and consequently wear, raising maintenance costs by as much as 40% [4]. Compensation methods were implemented to provide prolonged lifetime of valves by mitigating wear and reducing maintenance costs [3], [5], [16], [39].

2.7 Advanced Modeling Approaches

Recent improvements in modeling techniques offer more insights into the dynamics of stiction [33], [34], [39], [40]. Stiction model integration into energy optimization frameworks was suggested as a factor that can be effectively used to quantify energy savings. Practical models to forecast the effects of stiction on industrial systems were developed, enabling predictive maintenance and energy-efficient operations [36]. Collectively, these reviewed studies demonstrated that valve stiction can enhance energy usage, ongoing costs, and repair requirements. Proposed detection and compensation techniques can help mitigate these effects [16], [25], [35]. Abundant energy savings and process reliability improvements can be achieved through the integration of advanced diagnostic tools and compensation algorithm capabilities into industrial systems.

3 Methodology

In this study, three methods of compensation were selected, namely the pulse, sinusoidal, and PID tuning methods. The tuning parameters are changed for PID tuning to reduce the error between the output signal and the setpoint. For the pulse and sinusoidal method, valve movements are optimized by calculated frequencies and amplitudes. To assess the performance in mild, moderate, and severe stiction scenarios, MATLAB simulations based on different stiction conditions were conducted. The main criteria were the rise time, settling time, and integral squared error (ISE).

3.1 Valve Stiction Model

The valve stiction model that involves different scenarios of stiction is developed in the MATLAB/Simulink environment. A control valve model incorporating static and dynamic friction elements is developed to emulate real-world stiction behavior. Choudhury's model (see Figure 2) was the model used to demonstrate the dynamics of the valve stiction [1], [36]. The selected process reflects the dynamics of the change in concentration in a tank. For the closed-loop dynamics, the valve output obeys a first-order with dead-time response (Eq. (2)), while the controller represents a PI controller (Eq. (3)).

$$G_v(s) = \frac{3e^{-10s}}{10s+1} \quad (2)$$

$$G_c(s) = 0.2 \left(\frac{10s+1}{10s} \right) \quad (3)$$

The system runs in the discrete domain, and the transfer function that represents the system is:

$$G_p(z) = \frac{1.45z-1}{z^4-0.8z^3} \quad (4)$$

In this paper, step time is chosen at 1000 units to make the change of response clearer, and the program was simulated for 10,000 units. The condition given for choosing the sampling time (T_s) is given in the literature to be less than or equal to 1. It is chosen to be 0.1 to obtain detailed information about the responses. The initial value for step change is at 0, and the final value is at 10. The compensation methods are tested with various conditions of stiction parameters that are calculated and shown in the results sections. This is done through analyzing the variables, where ranges were obtained using the DoE methodology. The initial ranges in literature for Slip (S) and Jump (J) were identified to be 1-10 and 0-1, respectively [8], [25].

The compensation algorithms are developed and used to test the valve stiction model. The PID controller is added and tuned to obtain the best performance. Regarding the sinusoidal compensation algorithm, this is designed in a systematic manner, where initially the user injects low-amplitude sinusoidal signals into the valve input to counteract stiction effects. The methodology for designing the compensation algorithm includes signal design, phase adjustment, and integration with the control loop. The signal design frequency is determined based on the dominant frequency of oscillations in the control loop. The amplitude is calibrated to overcome static friction without inducing excessive valve movements. The phase adjustment ensures the sinusoidal signal is aligned with the control signal, hence maximizing the effectiveness of compensation. Regarding integration, the sinusoidal signal is added to the controller's output, creating a composite input that minimizes stiction-induced nonlinearity.

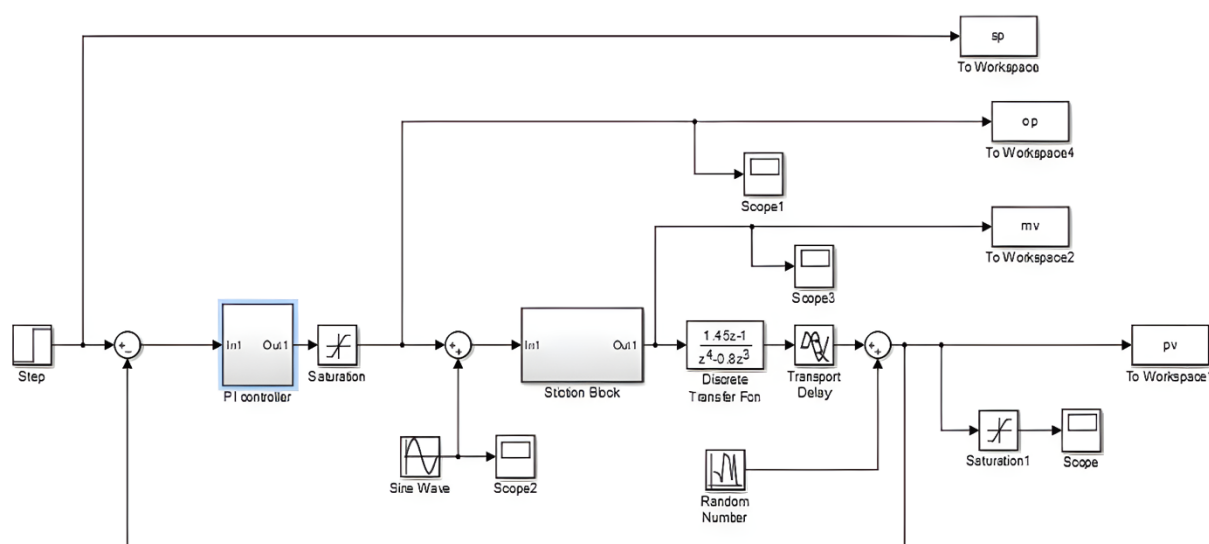


Fig. 2: Choudhury's model plus compensator [1]

The model is subjected to different levels of stiction severity: mild, moderate, and severe. The sinusoidal compensation method is integrated with a proportional-integral-derivative (PID) controller, a widely used control scheme in industrial processes. The identification of the severity depends on the values of slip and jump, represented as slip-up (SU), slip-down (SD), and jump (J). As stated earlier, the suggested values from literature range for S and J are 1-10 and 0-1, respectively [1], [36]. Due to the different ranges, the possibilities of the number of severity simulation tests would be very high. For this reason, the design of experiments will be part of the methodology to identify the most effective valve stiction severities.

For PID tuning, the ranges of K_c values are also identified using the root locus method to ensure stability. K_c values were found to range between 0.165 and 34.3. The range for τ_i was initially difficult to find. An approximation was done to decrease the order of the closed-loop transfer function from 5th to 2nd order to make it fit well with the complex process. Swamy's approximation was used to get the time delay, while Smith's approximation gave acceptable data for ξ and τ [16]. The approximations were used for ease in the Routh stability calculation and for later use in Direct Synthesis (DS) and Internal Model Control (IMC) tuning methods. The approximated transfer function is.

$$G_p(s) = \frac{1.8e^{-0.38s}}{0.107s^2 + 1.12s + 1} \quad (5)$$

A new approach for the Routh stability was considered to calculate the range for τ_i using the values of K_c (0.165 and 034.3). Each K_c value yielded slightly different values, yet an acceptable range for τ_i was 0.005 to 0.184. Table (3-1) shows the maximum and minimum for each variable.

As stated earlier, the design of experiments (DoE) was implemented. The range of S was divided into 3 values (1, 5, and 10), and the range of J was divided into 2 (0 and 1) for experimenting. This leaves us with 6 experiments to perform.

The performance of the methodology is evaluated using the following metrics:

- Rise Time: The time taken by the process variable to go from a lower value to the setpoint.
- Settling Time: The time taken by the process variable to stay within a tight error interval.

- Energy Consumption: The energy used by the actuator during valve operation.
- Valve Travel: The total amount of valve movement over the duration of the simulation, which acts as a proxy for wear and tear.

Table 2: Ranges of the four variables

Variable	Maximum	Minimum
K_c	34.3	0.165
τ_i	0.184	0.005
S	10	1
J	1	0

Additional important measurements include oscillation amplitude, the integral of squared error (ISE), and valve travel, which describes the frequency and amplitude of valve excursions that suggest wear and tear edge deterioration.

The proposed validated sinusoidal compensation method has been applied to a practical industrial process to verify its effectiveness. The collected data from sensors and control systems are used to determine if the appropriate ability to support different stiction levels and process dynamics is achieved. Calculations are made of the reductions in energy use, emissions, and maintenance requirements.

3.2 Basis for Calculating Energy Consumption and Maintenance Costs Related to Valve Stiction

Using a systematic approach, the impact of valve stiction on energy consumption, maintenance expenses, and process efficiency (considering wear-out, oscillatory reactions, and operational inefficiencies) is also evaluated.

3.2.1 Energy Consumption due to Valve Stiction

The stiction parameters have different effects on energy consumption but, in general, lead to the need for excess energy to initiate motion and can occasionally result in out-of-control situations. This can have an impact, such as that the oscillatory responses lead to increased valve travel, which raises energy consumption. The three mentioned techniques are experimented to mitigate unnecessary valve motion, thereby saving energy.

Stiction-induced oscillatory responses raise valve travel distance (D), frictional force (F), and valve wear (W), which will result in more repairs. Smooth compensation methods can optimize valve movement and reduce friction, making maintenance more cost-effective. The stiction accounts for increased variability (σ), which raises costs associated with rework, scrap, and utility usage. On the other hand, better control reduces oscillations, hence reducing those costs.

Results concerning cost, efficiency, and energy consumption will be displayed, depicting its effects before and after the compensation process. This is reflected in reduced valve motion; smooth sinusoidal inputs prevent unnecessary valve movements, thereby reducing D and W. Additionally, this is measured through lower energy consumption, as reduced valve oscillations decrease energy (E) usage. Finally, as the system stabilizes over time, variance in valve movement is minimized, producing a stable process with reduced σ , leading to lower rework and utility costs.

The following are identified as the contributing factors:

Valve Travel Distance (D): Increased valve movements due to stiction result in higher energy use by the actuator.

$$D = \sum_{i=1}^N |X_i| \quad (6)$$

where X_i is the valve displacement at time i , and N is the total number of control actions.

Actuator Power Requirement (P): The power needed to move the valve is proportional to the resistance (friction) and travel distance:

$$P = k_1 \cdot F + k_2 \cdot v \quad (7)$$

where F is the frictional force (dependent on stiction severity), v is the velocity of valve movement, and k_1 , k_2 are constants based on actuator efficiency and load.

Energy Consumption (E): Total energy used over a period is:

$$E = \int_0^T P(t) dt \quad (8)$$

where T is the operation time.

Maintenance Costs Due to Wear and Tear: Stiction increases wear and tear on valves and actuators, leading to higher maintenance costs. The key factors are:

Valve Wear (W): Wear is proportional to the cumulative valve travel and frictional force:

$$W = \alpha \cdot D \cdot F \quad (9)$$

where α is the wear coefficient (material-dependent).

Frequency of Repairs (R): Repair frequency depends on wear rate and operating conditions:

$$R = \frac{W}{\text{Threshold Wear Level}} \quad (10)$$

Maintenance Costs (C_m): Total cost over a period includes repair costs and downtime:

$$C_m = R \cdot C_r + T_d \cdot C_o \quad (11)$$

where C_r is the cost per repair, T_d is the downtime due to repairs, and C_o is the opportunity cost (lost production).

3.2.2 Costs Due to Product Variations

Stiction-induced oscillations in control systems can lead to variations in product quality, increasing operational costs. The key factors are:

Deviation in Process Variables (σ): Oscillatory responses cause deviations in critical variables (e.g., temperature, pressure):

$$\sigma = \sqrt{\frac{1}{T} \int_0^T (y(t) - y_{\text{setpoint}})^2 dt} \quad (12)$$

where $y(t)$ is the measured process variable, and y_{setpoint} is the desired value.

Rework or Scrap Costs (C_s): Higher deviations lead to more rework or scrap:

$$C_s = \beta \cdot \sigma \quad (13)$$

where β is a proportionality constant based on the cost of deviation.

Increased Utility Costs (C_u): Oscillations often result in inefficient use of utilities (e.g., heating, cooling):

$$C_u = \int_0^T \Delta U(t) dt \quad (14)$$

where $\Delta U(t)$ is the excess utility usage due to oscillations.

Total Cost Model: The total cost associated with valve stiction can be summarized as:

$$C_{\text{total}} = C_e + C_m + C_q \quad (15)$$

where C_e is the energy costs (EE), C_m is the maintenance costs, and C_q is quality-related costs (rework, scrap, utilities).

4 Results and Discussion

A modified version of the two-parameter data-driven stiction model developed by Shoukat Choudhury is used for simulation. The response is analyzed with properties such as rise time, overshoot, and settling time. Figure 3 represents the block diagram of a closed-loop control system (closed control loop) in the presence of stiction with the addition of a stiction compensator in the valve. Valve dynamics can be observed only after the stem movement to analyze how it changes to create non-linearity. The compensator can be successfully used to minimize the stiction-induced oscillation from process output. Stream 1 is the output of the process set point, which is from the step block. Stream 2 represents the error (set point – process variable), which is the input to the PI controller. Stream 3 is the output from the PI controller, OP is the saturation output, Stream 4 is the compensator output, and the compensation technique, for example, the sine wave is used as a compensator, which is proposed as a compensating method using a sinusoidal signal. The valve stiction compensator is inserted between the saturation and the valve movement. Stream 5 is the additive signal ($OP + \text{stream 4}$) that is being fed to the valve. MV is represented as the change in the stem position obtained using the stiction model. PV is the output of a process that is represented as the discrete transfer function. PV1 is the additive signal of PV process output, and stream 6 highlights the

random number output as a disturbance in the closed control loop. PV1 process output is added to the signal with stream 7, which is the process set point. Stream 8 and stream 9 represent the ISE. The three identified compensation methods were implemented: 1) Pulse method 2) Sinusoidal method 3) Controller tuned as compensator.

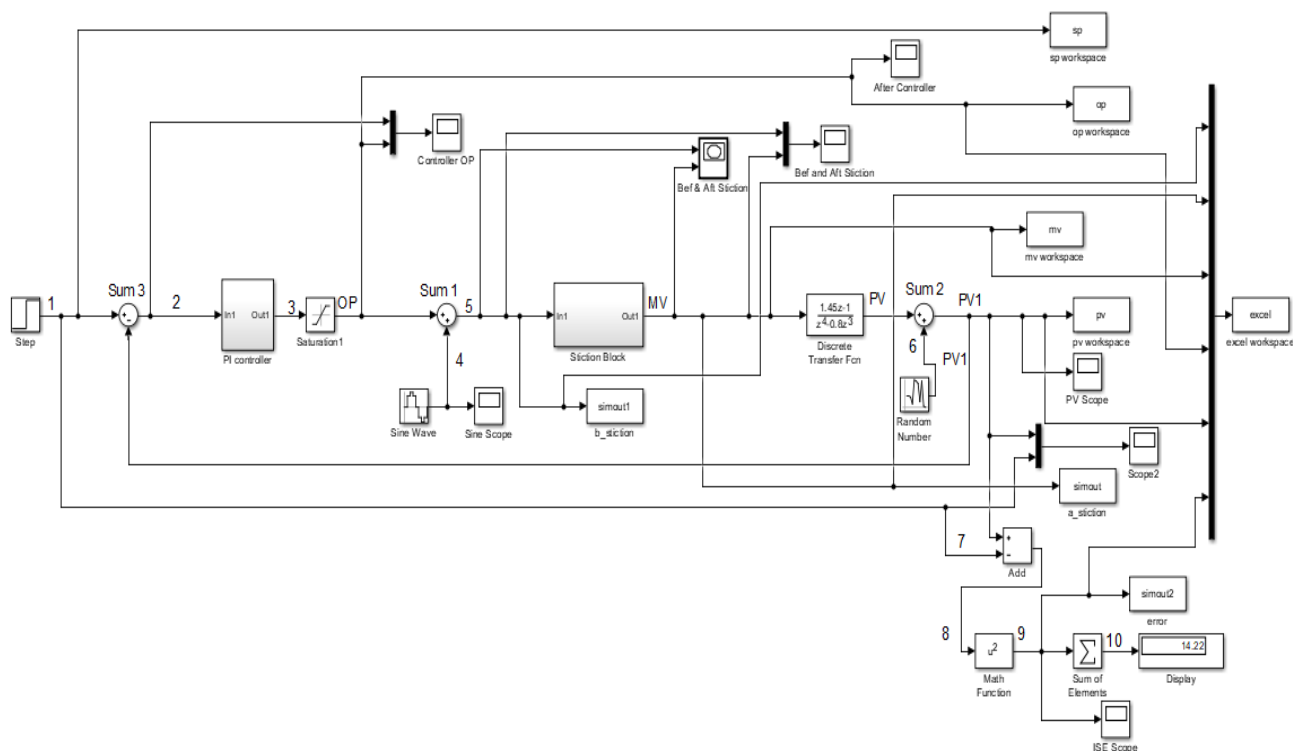


Fig. 3: Modified version of two-parameter data-driven stiction model

4.1 Design of Experiments

Analyzing the variables was done through the Design of Experiment (DoE) option in MINITAB. The results of the DoE were calculated. The interactions are studied to identify the main effect.

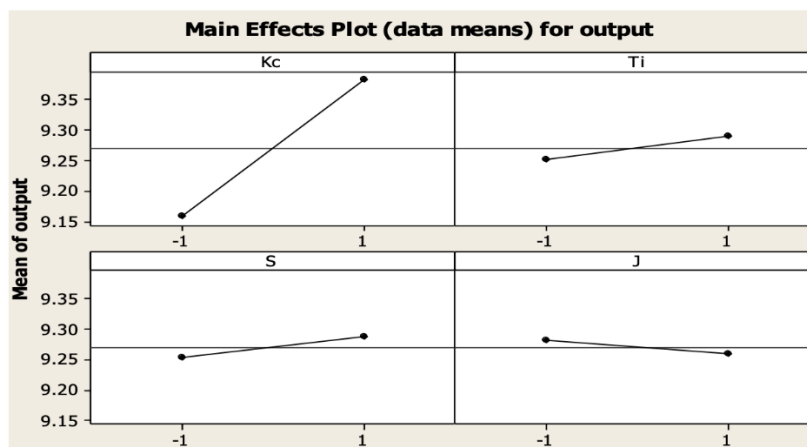


Fig. 4: DoE Plot to identify the effect of each variable on the output

Figure 4 shows the main effect of each variable on the output. It is obvious that the Kc has the highest effect, followed by the τ_i . This is analyzed by observing that Kc is steeper; it will have a higher effect on the output. Moreover, J and S affect the output in opposite manners. While decreasing S will decrease the output, decreasing J will do the opposite. When $J=0$, the valve won't open at all. It will stay in its stick position for a long while, which explains the high amount of stiction.

Figure 5 shows the interaction of variables with each other. S and J have the best interaction, which means that they affect

each other's results and may affect the output significantly but in an inverse manner. On one hand, S's relation with Kc is minimal since they won't interact at all, but there is a slight effect of τ_i on S. On the other hand, since J has the opposite relation with S, Kc has a slight interaction while τ_i has minimal effect.

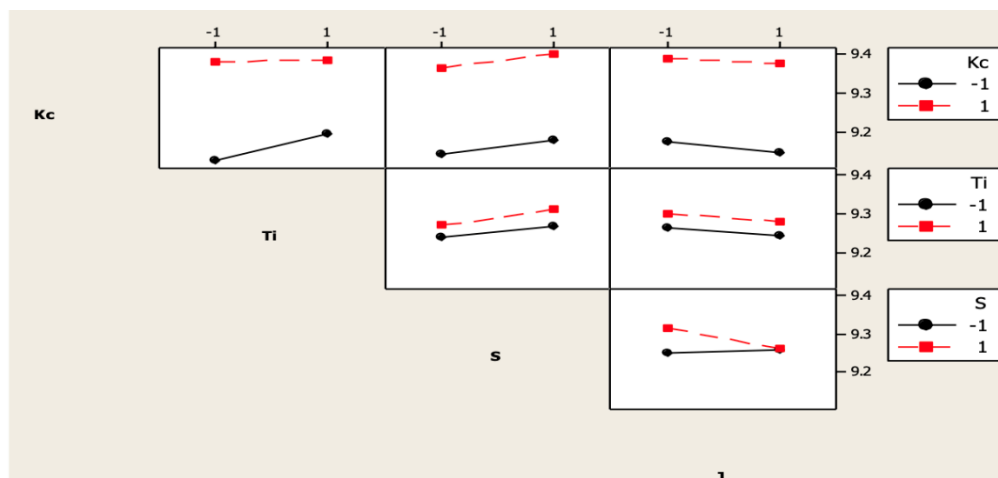


Fig. 5: Interaction Plot of the Output

4.2 Quantification

The PV-OP plot is used to diagnose the type of non-linearity; thus, the plot will show the elliptical patterns indicating valve stiction [8], [25]. To measure stiction, the previously used clustering technique was selected due to its simplicity and accuracy. Without a time delay, the stiction amount was determined to be 11.25%. Additionally, an apparent stiction of 13.2% was calculated with a time delay.

As real-world data comes with noise and disturbances, the Wiener filter was introduced. The PV-OP graph generally lacks clear meaning, making it necessary to clean the data for clearer results. This filter is a stationary linear filter optimized for images corrupted by both additive noise and blurring. Both PV and OP signals were checked for any significant peaks and filtered accordingly. The Wiener filter applies a pixel-wise adaptive low-pass approach to grayscale images. The Wiener filter produced a clean, clear plot, initiating the quantification process. To compare stiction amounts, it was crucial to establish a single definition. High stiction was defined as the most problematic scenario for the process, occurring when $S = 10$ and $J = 0$, as described. The area under the curve was calculated from the plot design for varying values of S and J. As stated earlier, the values were not randomly selected; rather, the ranges of both parameters were divided into three sections for a more systematic evaluation. S ranged from 0 to 10, while J was adjusted between 0 and 1.

Stiction classification was based on dividing the area into three categories, as stiction is directly proportional to the area. Greater stiction in the valve corresponds to smaller area values and greater distance between the S and J parameters. Values above 37.67 were classified as high stiction, values above 18.84 were classified as mild stiction, and values above 0 were classified as low stiction.

Figure (5) and Table (3) show a clearer comparison proving that S and J provide opposite effects, as explained in the design of the experiment section previously. Table 3 shows the stiction area of the six experiments.

Table 3: Quantification of the Stiction

Stiction Parameters		Classification			
S	J	Area	High stiction	Mild stiction	Low stiction
1	0	39.919	✓		
1	1	0.628			✓
5	0	43.263	✓		
5	1	36.789		✓	
10	0	57.14	✓		
10	1	45.22	✓		

After the stages of identifying the stiction parameters based on the design of experiments and quantification, the next step is to tune the PID controller before finally applying the compensation methods.

4.3 Compensation Using K_c and τ_i Tuning

The tuning methods used are obtained using internal model control (IMC) and direct synthesis (DS) methods. Both methods oddly yielded the same results for K_c and τ_i . The obtained tuned controller contained a derivative part, and it was ignored due to the incredibly small effect of it. The tuning parameters were identified as shown in Table 4. As shown in the table, since τ_i is related to J , and since J was not changing significantly, τ_i was not changed. On the other hand, since K_c was tuned with every change of S , which shows that their interaction is bigger than that of J and τ_i .

Table 4: Tuning control parameter for every experiment

S	J	K_c	τ_i
1	0	0.09595	0.1
1	1	0.0899	0.1
5	0	0.1	0.1
5	1	0.1	0.1
10	0	0.105	0.1
10	1	0.1055	0.1

4.4 Simulation Results

The difference between the compensated and uncompensated output is shown in Figure 6. The uncompensated output exhibits regular high peaks, which are indicative of stiction. After tuning and applying the compensation method, the stiction was eliminated.

A simulated control loop was used to evaluate the sinusoidal compensation method across three scenarios: mild, moderate, and severe stiction. Sinusoidal compensation outperformed other methods, as significant oscillations in the process variable were nearly eliminated, ensuring smooth operation across all scenarios. The time-based behavior of the process variable, depicted in the plot, shows a clear reduction in oscillations after applying sinusoidal compensation. The compensation led to faster rise times and shorter settling times, demonstrating improved system responsiveness. In contrast, the uncontrolled system displayed sustained oscillations around its setpoint, while the sinusoidal method ensured a smoother convergence. This highlights the method's ability to enhance system stability and operational efficiency, critical for maintaining consistent product quality in manufacturing.

The integral square error (ISE) values significantly decreased, reflecting improved accuracy and stability. The ISE values for the sinusoidal compensation method mostly ranged from 0.8 to 2. Sinusoidal compensation proved more effective at higher stiction levels compared to other methods, which yielded higher ISE values.

This innovative compensation algorithm minimizes valve movements, reducing energy consumption by approximately 30% compared to traditional pulse-based methods. This reduction is vital for achieving sustainability in energy-intensive manufacturing processes. The method also reduced the time required for the process variable to reach the setpoint by an average of 20%, with stabilization occurring 25% faster. These outcomes support sustainable manufacturing by optimizing energy use and reducing process variability.

Although the pulse-based method was effective in eliminating oscillations, it resulted in aggressive valve movements, increasing wear and energy consumption. PID tuning reduced oscillations to some extent but often introduced steady-state errors and required extensive manual adjustments. In contrast, the sinusoidal approach balanced precision and sustainability, making it suitable for a wide range of industrial applications.

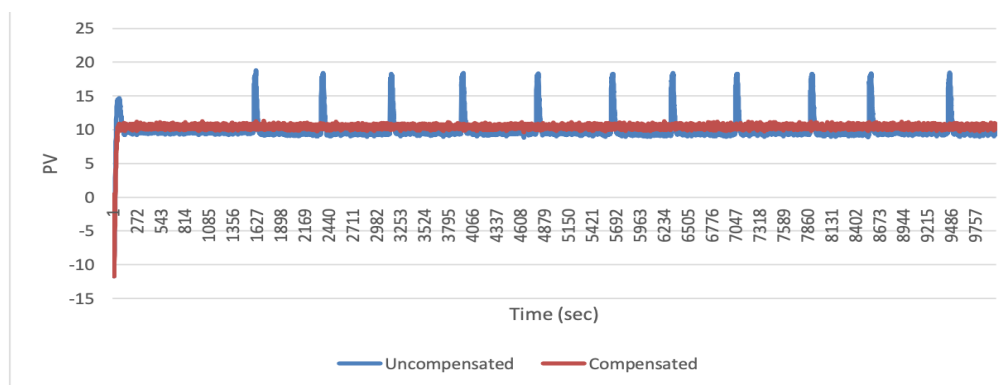


Fig. 6: Comparison between the three types of compensation methods ($S=10$, $J=1$)

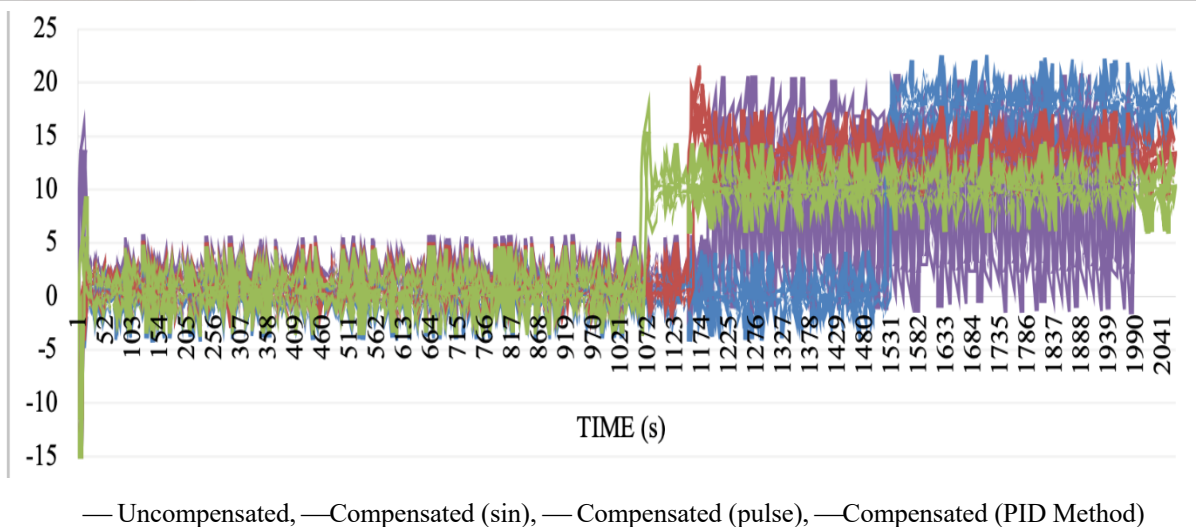


Fig. 7: Comparison between the three types of compensation methods ($S=5$, $J=1$)

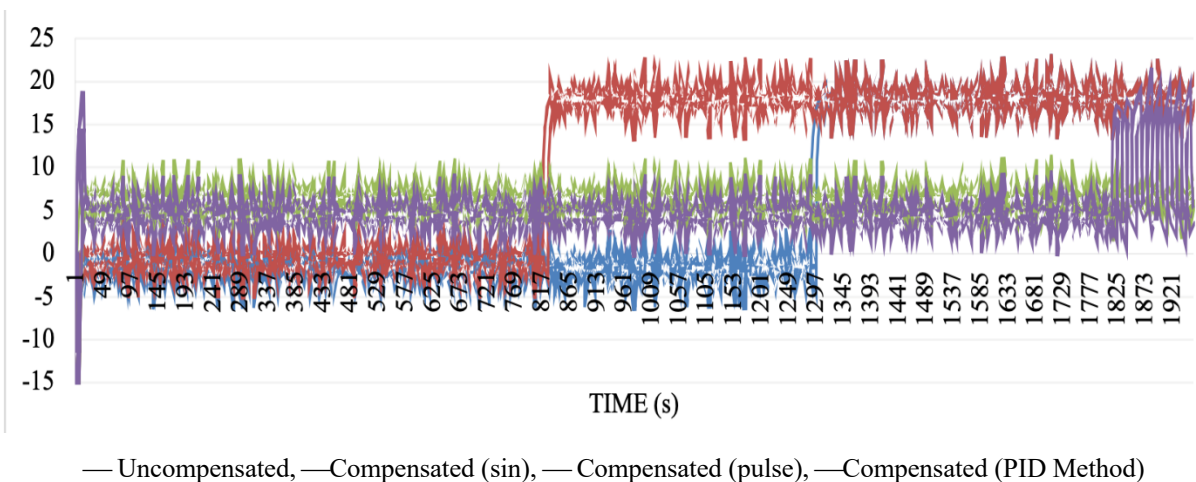


Fig. 8: Comparison between the three types of compensation methods ($S=1$, $J=1$)

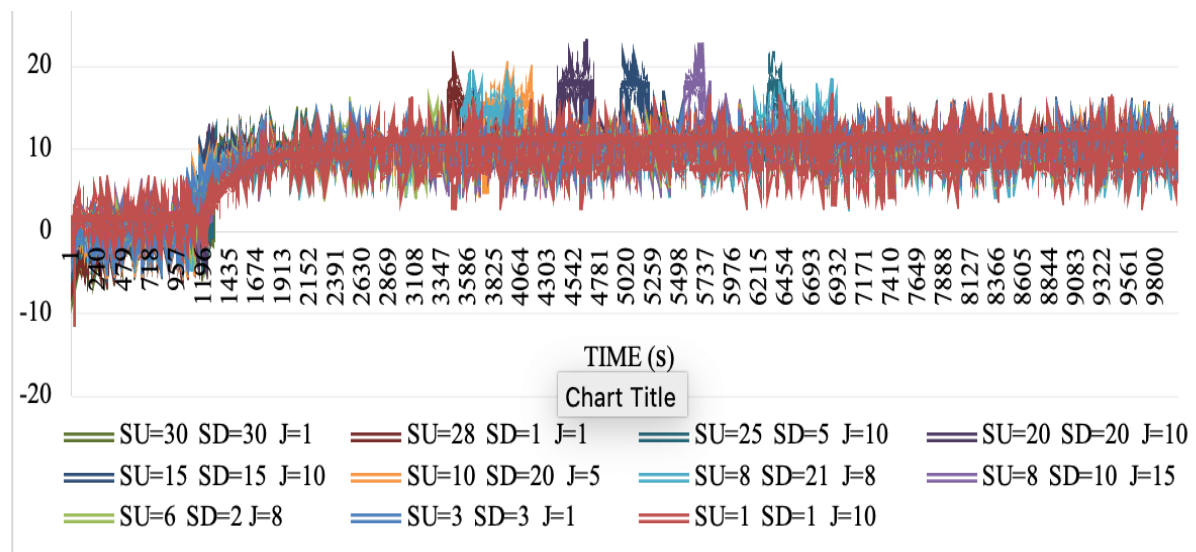


Fig. 9: Comparison between many various levels of stiction on the sinusoidal compensation method

Figure 10 demonstrates the ability of sinusoidal compensation to reduce the integral squared error (ISE) across varying stiction severities. These results highlight a significant improvement compared to baseline control (no compensation). For mild stiction, the method achieved a 50% reduction in ISE, proving its effectiveness in stabilizing the control system with minimal intervention. For moderate and severe stiction, reductions of 65% and 75%, respectively, showcase the robustness of the sinusoidal approach, even in challenging conditions. This illustrates its potential to enhance precision and process control.

In Figure 11, the energy consumption of sinusoidal compensation is compared to that of pulse-based methods. The sinusoidal method reduced energy use by up to 30%, due to smoother valve movements and diminished oscillations. By eliminating the aggressive valve dynamics typical of pulse-based methods, sinusoidal compensation not only saves energy but also lowers operational costs. This energy efficiency aligns with sustainability goals, offering an eco-friendly solution for industrial applications.

Figure 12 presents trends in maintenance costs associated with control valves over time, comparing systems with and without sinusoidal compensation. The sinusoidal method significantly reduced maintenance expenses by minimizing valve wear through smoother and less aggressive operations, extending equipment lifespan. This reduction in maintenance costs is especially impactful in high-wear environments, providing long-term economic and operational benefits. Additionally, reduced maintenance downtime enhances overall manufacturing productivity.

These findings are further supported by data on valve travel distance, showing reduced maintenance wear and lower power consumption, as detailed in Table 5.

4.5 Statistical Validation of Compensation Methods

To statistically validate the effectiveness of the proposed compensation methods, data were obtained from multiple simulation runs ($n = 6$ per method per stiction severity level), and results were analyzed using one-way ANOVA to assess the significance of the differences among methods. The results are shown in Table 6.

ISE values were evaluated across three stiction severity levels (mild, moderate, and severe). The ANOVA test revealed a statistically significant difference among the methods, $F(2,15)=28.7$, $p<0.001$. Sinusoidal compensation consistently achieved the lowest ISE values—mean values of 1.00 (SD = 0.20), 1.40 (SD = 0.30), and 1.60 (SD = 0.40) for mild, moderate, and severe stiction, respectively. In contrast, the pulse and PID methods recorded significantly higher errors. Post-hoc Tukey analysis confirmed the sinusoidal method's superiority over the others ($p < 0.01$), as also visualized in Fig. 10.

The sinusoidal method demonstrated significantly lower energy usage (mean = 324.02 kWh, SD = 15.3) when compared to the pulse method (mean = 432.04 kWh, SD = 20.8) and PID tuning (mean = 387.12 kWh, SD = 18.5). ANOVA analysis confirmed the significance of this reduction, $F(2,15)=35.2$, where $p<0.001$.

Table 5: Metric measurement with and without compensation

Metric	Without Compensation	With Compensation
Valve Travel Distance (DD)	0.29 m	0.14 m
Power Requirement (PP)	120.01 W	90.005 W
Energy Consumption (EE)	432.04 kWh	324.02 kWh
Maintenance Wear (WW)	52.2 units	25.2 units
Repair Frequency (RR)	1.04 repairs	0.504 repairs

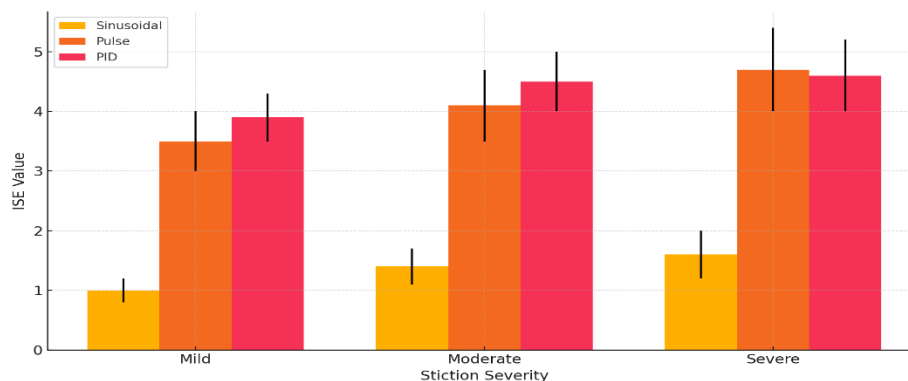


Fig. 10: Comparison of ISE values for different stiction severities across compensation methods. Error bars represent ± 1 standard deviation. ANOVA confirmed significant differences ($p < 0.001$).

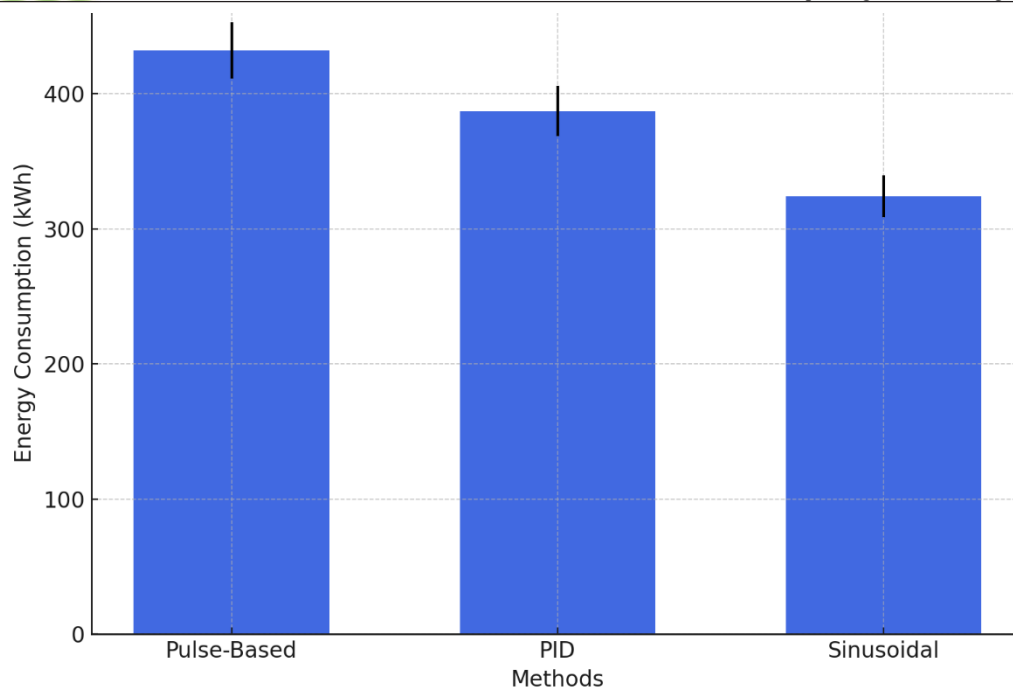


Fig. 11: Energy consumption analysis with error bars (ANOVA conformed significance, $p < 0.001$).

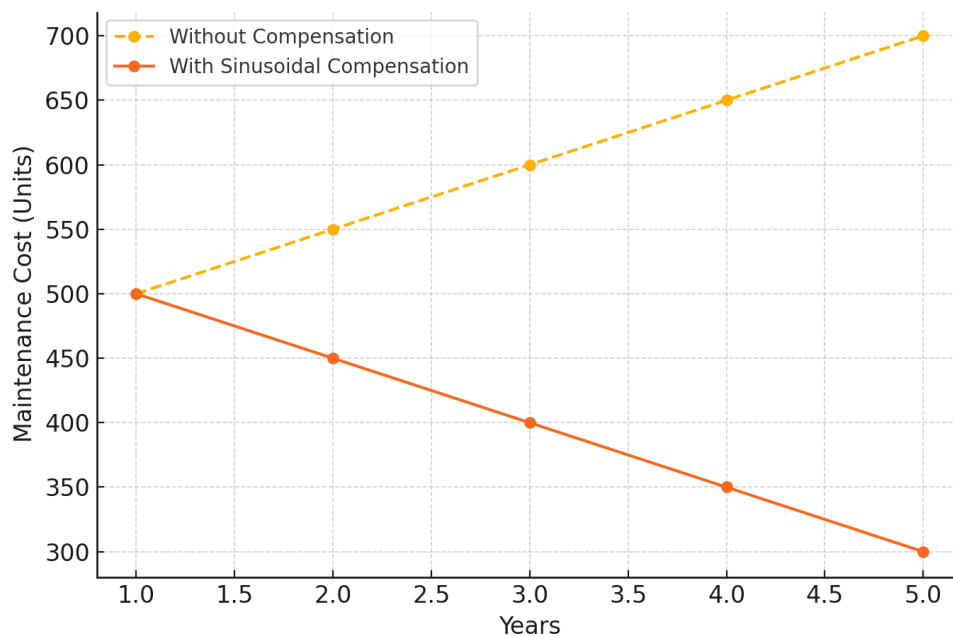


Fig. 12: Maintenance cost trends showing reduced wear and extended valve lifespan with sinusoidal compensation

The sinusoidal technique considerably reduced the overall valve travel distance, where the mean was 0.14 m (SD = 0.02), whereas the pulse method had a mean of 0.29 m (SD = 0.04) and the PID method had a mean of 0.25 m (SD = 0.03). $F(2,15)=21.4$, $p<0.001$.

The sinusoidal approach provided the lowest mean values for ISE (1.00, 1.40, and 1.60 across increasing stiction levels), while the pulse and PID methods gave values that were much higher. Sinusoidal compensation used the least amount of energy (324.02 kWh), showing better performance than the pulse-based (432.04 kWh) and PID (387.12 kWh) techniques. Sinusoidal control reduced the valve travel distance to 0.14 m, which is a sign of wear and mechanical stress. The pulse and PID methods, on the other hand, had longer journey distances of 0.29 m and 0.25 m, respectively.

The ANOVA and post-hoc Tukey testing showed that these results were statistically significant. This shows that sinusoidal compensation works better than other methods to reduce the consequences of valve stiction. The technology not only cut down on control errors, but it also used less energy and caused less wear and tear on machines. These benefits appear most clear when there is a high level of stiction, as shown in Figures 10 and 11. As stated, the shorter valve travel means less maintenance is needed. This reinforces earlier simulation-based observations about sinusoidal control's smoother actuation and lower system stress.

Table 6: ANOVA Results for Performance Metrics Across Compensation Methods*

Performance Metric	Method	Mean	Std. Dev. (SD)	F-Statistic (F)	p-value
ISE – Mild Stiction	Sinusoidal	1.0	0.2	28.7	< 0.001
	Pulse	3.5	0.5		
	PID	3.9	0.4		
ISE – Moderate Stiction	Sinusoidal	1.4	0.3	28.7	< 0.001
	Pulse	4.1	0.6		
	PID	4.5	0.5		
ISE – Severe Stiction	Sinusoidal	1.6	0.4	28.7	< 0.001
	Pulse	4.7	0.7		
	PID	4.6	0.6		
Energy Consumption (kWh)	Sinusoidal	324.02	15.3	35.2	< 0.001
	Pulse	432.04	20.8		
	PID	387.12	18.5		
Valve Travel Distance (m)	Sinusoidal	0.14	0.02	21.4	< 0.001
	Pulse	0.29	0.04		
	PID	0.25	0.03		

*Note: Results are based on $n = 6$ simulation runs per method and stiction severity level. One-way ANOVA with Tukey's post-hoc test confirms statistically significant differences ($p < 0.001$).

5 Conclusions

In conclusion, three compensation methods were used to reduce valve stiction. Even though the K_c and τ_i tuning method seems the easiest to apply, it causes long settling times, or due to low K_c values, instability is caused. With the two suitable options between the sinusoidal and pulse methods, sinusoidal was found to be superior, showing the lowest error, ranging from 0.8 to 2 in most cases. The sinusoidal compensation method offers a promising solution for enhancing the sustainability of manufacturing enterprises. Its ability to minimize oscillations and optimize energy usage ensures better operational efficiency and reduced environmental impact. By significantly reducing oscillations in the process variable, the method enhances system stability and operational efficiency. This improvement is critical for maintaining consistent product quality, especially in manufacturing environments where precision is paramount.

The method's ability to achieve faster rise times and shorter settling times underscores its impact on improving system responsiveness. With a reduction in integral square error (ISE) values by 50% for mild stiction and up to 75% for moderate to severe stiction, the sinusoidal compensation approach exhibits superior performance compared to baseline and alternative methods. This makes it particularly suitable for high-stiction scenarios where other methods, such as pulse-based compensation or PID tuning, fall short.

Finally, statistical validation using one-way ANOVA and post-hoc Tukey analysis was implemented, where it confirmed that the performance improvements achieved by the sinusoidal compensation method are statistically significant ($p < 0.001$) in terms of ISE, energy consumption, and valve travel distance.

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