COMPENSATION OF CONTROL VALVE STICTION

MASTER OF SCIENCE IN ENGINEERING
(CHEMICAL)

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AUGUST, 2012

CERTIFICATION OF THESIS WORK

We the undersigned, are pleased to certify that **B. M. Sirajeel Arifin**, a candidate for the degree of **Master of Science in Engineering (Chemical)** has presented his thesis work on the subject **"Compensation of Control Valve Stiction"**. The thesis is acceptable in the form and content. The student demonstrated a satisfactory knowledge of the field covered by this thesis in an oral examination held on **August 13, 2012**.

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ABSTRACT

Valve stiction is the hidden culprit of the process control loop. Among all nonlinearities of control valve, stiction has been being one of the major valve problems since the past two decades. Over the last two decades, several well established methods have been developed for detection and quantification of stiction. But methods for stiction compensation are still in developing stage. Among the existing two methods of stiction compensation, the 'Knocker' method is the most popular one. The other method known 'two move' method is yet to be applied in the process industries. Inverse stiction method in presence of saturation is another method which will require pilot plant study. However though PID controllers are inherent part of modern process industries, no noticeable work is yet done to compensate valve stiction through PID controller tuning. In this study, a novel approach to compensate stiction by using a PID controller was studied. A Second Order Process with Time Delay (SOPTD) was chosen for the study. Stiction was simulated by using the two parameter stiction model. It was confirmed that the Integral part of a controller has adverse effect on stiction. It was noteworthy that the derivative part of a controller has no effect on stiction. An empirical correlation was developed to relate the Proportional gain with the process parameters through extensive simulation for varying process parameters and controller gains. This empirical relation was evaluated for a large number of SOPTD processes. These results reveal that the correlation works well for process gain 2 to 5. It also works up to a gain of 10, if time delay is small. It is inspiring that stiction can be handled with a proportional only controller with the cost of some offset.

More investigations on proportional only controller has revealed that a low fixed value proportional controller can handle SOPTD with high gains. However, to remove the offset problem, using a very high integral time gives satisfactory results. A guideline for efficient tuning of the PID controller to handle stiction was also proposed which might act as the starting point of tuning a PID controller in presence of a sticky valve in the control loop.

Inverse stiction method was developed with the help of the two parameter stiction method in the later part of the study, which works both in parallel and series combination with the sticky valve. Both combinations nullify the oscillation caused by the presence of stiction. But application of the parallel inverse stiction method has practical limitations. Series inverse stiction has got the importance for further evaluation through pilot plants and process plant tests. Application of a dither signal to compensate stiction was also re-investigated and it was found that for pneumatic valve, adding dither signal with the controller signal is not practically possible due to its faster dynamics. Applying physical dither by creating continuous vibration in the valve packing region can be an option for future work.

ACKNOWLEDGEMENTS

This dissertation would not have been possible without Dr. M. A. A. Shoukat Choudhury who not only served as my supervisor but also encouraged and challenged me throughout this research. His continuous guidance and counseling enhanced my knowledge in this area as well as inspired me to continue my future work in this field of study.

The author would like to acknowledge Mr. Monir Ahammad, Ex- Lecturer, Department of Chemical Engineering, BUET for sharing his knowledge and also supporting all through this thesis work.

The author would also like to thank his family for their nonstop support and encouragement.

The author's final gratitude goes to the almighty Allah for enabling him to complete this work.

B. M. Sirajeel Arifin

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ABREVIATIONS and SYMBOLS

ABB	Swiss-based high-tech engineering multinational conglomerate
ANSI	American National Standards Institute
CSTR	Continuous Stirred Tank Reactor
D	Derivative
d	dead band/stick band for one parameter stiction model
DCS	Distributive Control System
DIRECT	(DIvide RECTangle method)
F_k , f_k	Compensator signal
FOPTD	First Order Plus Time Delay
G_p	Process Transfer Function
G_C	Controller Transfer Function
h_k	Time between each pulse
IAE	Integral Absolute Error
IMC	Internal Model Control
ISE	Integral Square Error
ISA	Instrument Society of America
J	Slip-jump
Kc, K_c	Controller gain
Kcm, K_{cm}	Controller gain calculated by proposed Correlation (equation 3.5)
Kci, K_{ci}	Controller gain calculated by IMC method
Kp, K_p	Process Gain
kp	Joint Process
MV	Manipulated Variable
OP	Controller output or Valve Input
OF	Objective Function
PI	Proportional Integral
PID	Proportional Integral Derivative
PV	Process Variable
S	Dead band plus Stick band for two parameter stiction model
SP	Set Point
SOPTD	Second Order Plus Time Delay
t_p	Time of onset of the previous pulse
T_m	Time interval required for the stabilization of the PV
T_p	Period of Oscillation
θ	Process Time Delay
u_c	Controller output
u_{cf}	Filtered signal from controller output
u_k	Output from the knocker
y	Process output
a,α	Amplitude
ω	Frequency
τ	Pulse width, Process time constant

Chapter 1

Introduction

1.1 Background

Stringent environmental regulations, constrained resources of energy and hard competition among the different entrepreneurs have made the process industries to be operated in maximum efficiency in terms of energy and raw material utilization, optimal quality of main products and by-products and safety of the plant personnel and surrounding human and other biological communities with a lower cost. To achieve better safety feature, product quality and efficiency in energy and raw material usage, most of the modern plants are now being increasingly automated. Control loops are the essential part of the automation process and in large process plants there are hundreds even thousands of control loops.

The automated processes reduce human involvement in the final control step by letting the control loops to take care of the movement of the valve, the final control element, according to the decision from the microprocessor, the controller, which takes the decision based on the differences between the measured process variable and the desired set point. In this automated process, a human operator just defines the desired set point and observes that the automatic controller is taking the proper steps to reduce the offset (difference between the measured variable and the desired set point). Figure 1.1 shows a Simple Feedback Control Scheme.

But what happens, if the control loop suffers from poor performance due to the non-linearity or oscillation of the controlling elements themselves? Performance of 26,000 PID from a wide range of continuous process industries were under investigation for 2 years by Desborough and Miller[1]. Figure 1.2 is the result of that investigation. In this investigation, various control loops were classified into five categories – excellent, acceptable, fair, poor and open loop based on minimum variance and oscillation criteria. The investigation shows that the performance of 68 % of the installed control loops is not satisfactory [2].

Industrial surveys of the past decade show that only one third of industrial controllers provide acceptable performance. Presence of oscillation causes a loss of energy and product quality and reduction of profitability is the ultimate consequence [3]. Oscillation can be caused by both physical and non-physical reasons. Among the non-physical reasons – a ggressive tuning of controller, loop interactions and presence of oscillatory disturbances are the main sources of oscillations. Sensor failure and control valve problems are the two main physical reasons of oscillation.

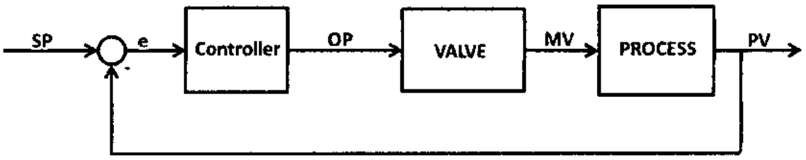


Figure – 1.1 : *A Simple Feedback Control Scheme*

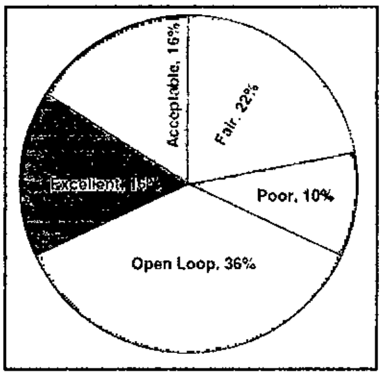


Figure – 1.2 : *Global Multi-Industry Performance Demography (Desborough and Miller, 2002)*

Control valve problems should be given a major importance because around 20-30 percent of all the control loops oscillation problems are due to control valve stiction and other valve non-linearities like Hysteresis, Deadband and Dead Zone. Among the many types of nonlinearities in control valves, stiction is the most common and one of the long-standing problems in the process industry for the spring-diaphragm type valves, which are widely used in the process industry. Stiction hinders proper movement of the valve stem and consequently affects control loop performance. Stiction is caused by the static friction between the valve stem and packing and a sticky valve wants to retain its stationary state till a sufficient amount of controller signal is applied when the valve moves past the desired point and then again when the controller signal is reversed to take the stem in the right position, the same effect happens again. In this way, a sustainable limit cycle is introduced in the process. Limit cycles are oscillation with well – defined amplitudes and periods. Since this is completely a physical problem; it can only be repaired when the plant is shutdown which generally takes place every two or three years during overhauling. In this long period, the valve operates sub-optimally which adversely deteriorate the product quality and profitability.

There are several methods for detection and quantification of stiction but only a few methods for stiction compensation. Stiction compensation methods help to operate a sticky valve with the minimum effect of stiction till the next overhauling. So at present, methods for compensations are of great importance for the control engineers. Among the few methods of compensation the Knocker method by Hugglund [4] is one of the best methods. Various modifications of this method are later described by [3] and [5]. Besides, the two move method offered by [6] is a recent approach for compensating stiction. In this study, two new methods of stiction compensation have been developed.

1.2 Objectives of this Study

1. Studying the different available control valve stiction techniques.
2. Developing a new technique for stiction compensation.

1.3 Scope of This Study

In this study, at first it was tried to develop a stiction compensation method by using a PID controller only. It is observed that Integral action has adverse effect on stiction as notified by [7]. It is also observed that derivative action has no effect on stiction. Later, a model to predict a proper Proportional only controller to compensate stiction for a given SOPTD (Second Order plus Time Delay) process was derived. The model was later simulated for different process models. Though the model was good for a broad range, but it does not work well for process gain of 5. So, few improvements were tried. Very low value of proportional controller reduces the amplitude of stiction but it also causes some offset, since it is the inherent property of a proportional only controller. So, it was tried to introduce a very low value Integral part. It is interesting to note that a very high step change gives good result. So, effect of change of step was also studied. In the later part, an inverse stiction method was attempted which showed good result in nullifying effect of oscillation, caused by stiction in both series and parallel combination with sticky valve.

1.4 Outline of the Thesis

Chapter 1 is the introduction to the thesis. It describes background, objective, scope and outline of the thesis.

Chapter 2 defines stiction. In this chapter the causes for stiction are discussed. The available compensation techniques are also reviewed in this chapter.

Chapter 3 describes the effect of PID controller on Stiction. It also shows some simulation results on different combinations of PID controllers. A Proportional only model is also proposed for combating stiction. Some modifications of the proposed method, by using very low proportional only controller and very high integral time, are discussed in the later part of this chapter.

Chapter 4 describes an alternative approach for combating stiction namely **Inverse Stiction** method. Simulation results are shown for this approach. Again dither method is revisited at the later part of this chapter.

Finally Chapter 5 draws the conclusion and recommendations for future work.

Chapter 2

Literature Review

2.1 Formal Definition of Stiction

The word stiction comes by combining two words – **static** and **friction.**

Generally it refers to the static friction of the valve stem which hinders it from moving until a definite amount (which is generally referred as % stiction) of controller output signal comes which causes the actuator to overcome the effect of static friction and due to the integral effect of the controller output, a sudden jump (slip jump) occurs in the valve positioner [2].

Before writing the definition of Stiction, definition of some related terms are given below as defined by ANSI [8] -

Backlash: "In process instrumentation, it is a relative movement between interacting mechanical parts, resulting from looseness, when the motion is reversed".

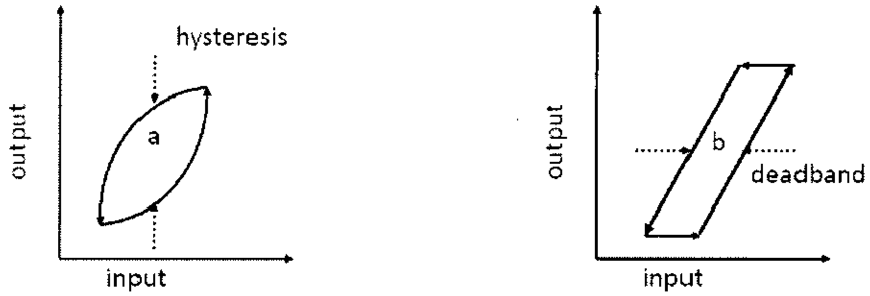
Hysteresis: "Hysteresis is that property of the element evidenced by the dependence of the value of the output, for a given excursion of the input, upon the history of prior excursions and the direction of the current traverse."
– "It is usually determined by subtracting the value of deadband from the maximum measured separation between upscale going and downscale going indications of the measured variable (during a full range traverse, unless otherwise specified) after transients have decayed."

Deadband*:* "In process instrumentation, it is the range through which an input signal may be varied, upon reversal of direction, without initiating an observable change in output signal."
– "There are separate and distinct input-output relationships for increasing and decreasing signals (See Figure 2.1(b))."
– "Deadband produces phase lag between input and output."
– "Deadband is usually expressed in percent of span."
Deadband and hysteresis may be present simultaneously. Figure 2.1(c) shows that case.

Some reversal of output may be expected for any small reversal of input. This distinguishes hysteresis from deadband." Figure 2.1(a) and 2.1(c) illustrate the concept.

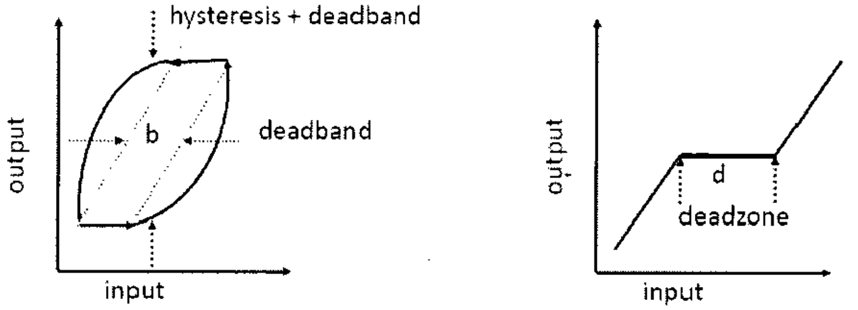
Dead zone*:* "It is a predetermined range of input through which the output remains unchanged, irrespective of the direction of change of the input signal."

– "There is but one input-output relationship (Figure 2.1(d))."
– "Dead zone produces no phase lag between input and output."



(a) hysteresis

(b) deadband



(c) hysteresis + deadband

(d) deadzone

***Figure 2.1** : Input- Output behavior of hysteresis, deadband and dead zone.*

2.2 The Definitions of Stiction [2]

- According to the Instrument Society of America(ISA), "stiction is the resistance to the start of motion, usually measured as the difference between the driving values required to overcome static Friction upscale and downscale" [8].

- According to Entech [9], "stiction is a tendency to stick-slip due to high static friction. The phenomenon causes a limited resolution of the resulting control valve motion. ISA terminology has not settled on a suitable term yet. Stick-slip is the tendency of a control valve to stick while at rest, and to suddenly slip after force has been applied".

- According to Horch [10], "The control valve is stuck in a certain position due to high static friction. The (integrating) controller then increases the set point to the valve until the static friction can be overcome. Then the valve breaks off and moves to a new position (slip phase) where it sticks again. The new position is usually on the other side of the desired set point such that the process starts in the opposite direction again".

- Ruel [11] defined, "stiction as a combination of the words stick and friction, created to emphasize the difference between static and dynamic friction. Stiction exists when the static (starting) friction exceeds the dynamic (moving) friction inside the valve. Stiction describes the valve's stem (or shaft) sticking when small changes are attempted. Friction of a moving object is less than when it is stationary. Stiction can keep the stem from moving for small control input changes, and then the stem moves when there is enough force to free it. The result of stiction is that the force required to get the stem to move is more than the required force to go to the desired stem position. In presence of stiction, the movement is jumpy."

- Olsson [12] defined Stiction as "short for static friction as opposed to dynamic friction. It describes the friction force at rest. Static friction counteracts external forces below a certain level and thus keeps an object from moving".

  The above discussion reveals the lack of a formal and general definition of stiction and the mechanism(s) that cause(s) it. All of the above definitions agree that stiction is the static friction that prevents an object from moving and when the external force overcomes the static friction the object starts moving. However, these definitions disagree in the way stiction is measured and how it can be modeled [2].

- Also, there is no clear description of what happens at the moment when the valve just overcomes the static friction. To overcome all these limitations a new definition was proposed by [2] :

  "The presence of stiction impairs proper valve movement, i.e. the valve stem may not move in response to the output signal from the controller or the valve positioner. The smooth movement of the valve in response to a varying input from the controller or the valve positioner is preceded by a stick band and an abrupt jump termed as slip-jump. Its origin in a mechanical system is static friction, which exceeds the dynamic friction during smooth movement of the valve."

Figure 2.2 represents the typical input–output behavior of a sticky valve. This phase plot can be divided into four phases - deadband, stickband, slip-jump and the moving phase. When the valve comes to rest or changes direction at point A in Fig. 2.2, the valve sticks and it remains at sticky until the controller output overcomes the deadband (AB) and the stickband (BC) of the valve. Then the valve jumps to a new position (point D) and continues to move. Due to very low or zero velocity, the valve may stick again between points D and E in Fig. 2.2 while travelling in the same direction.

2.3 Mechanism of Stiction

Friction in the valve arises principally in the packing (See Figure 2.3). It is the packing that stops process fluid from leaking out of the valve but the valve stem nevertheless has to move freely relative to the packing. There is a trade-off because too tight packing reduces emissions and leaks from the valve but at the same time increases the friction. Loose packing reduces friction but there is a potential for process fluids to leak. Other effects that cause excessive friction are corrosion of the valve stem, which makes it rough or nonsmooth, and deposits on the valve seat, which can make the valve plug stick in the seat.

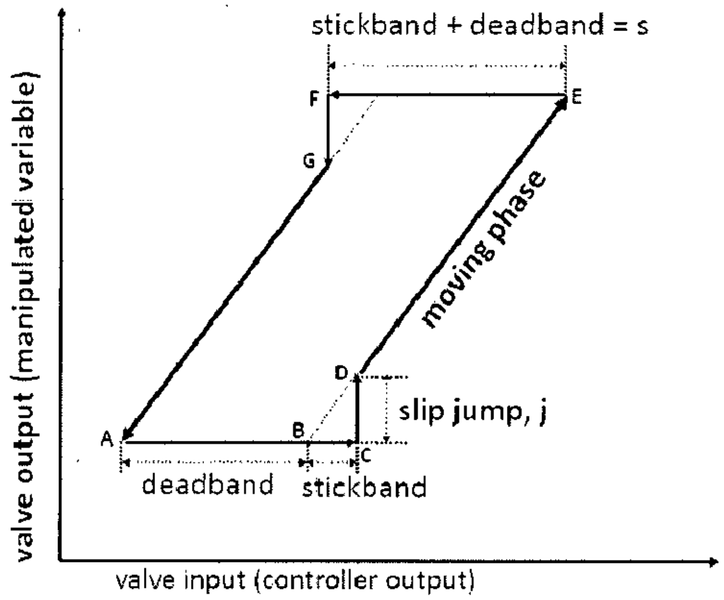


Figure 2.2 *: Typical input-output behavior of a sticky valve.*

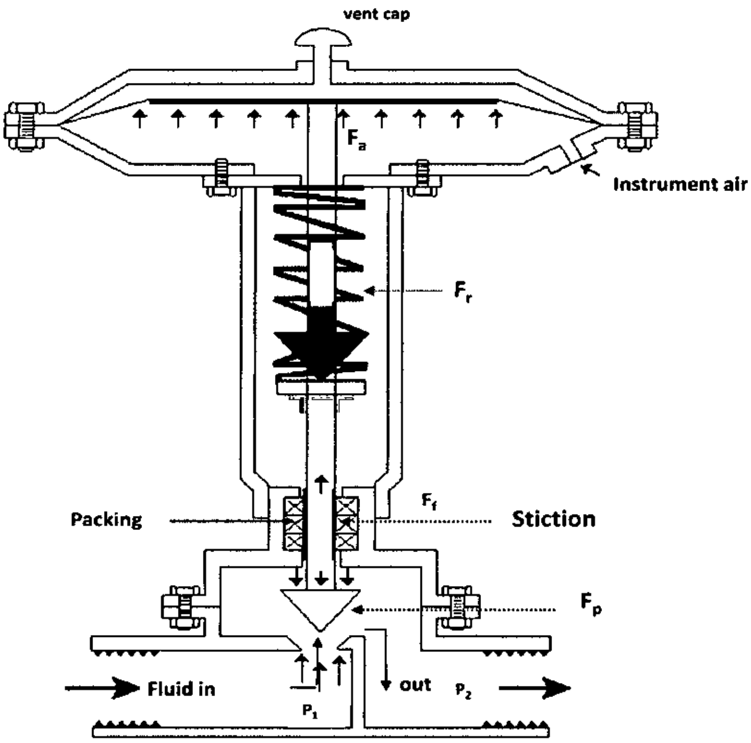


Figure 2.3 *: A cross-sectional diagram of a spring-diaphragm pneumatic control valve.*

2.4 Compensation of Stiction-General Approaches

Stiction compensation has got ultimate importance among the experts of different fields including the physicists, control engineers, tribologists, lubrication experts and so on. Several approaches have been reported for stiction compensation of servo-systems [13]. Armstrong-Helouvry *et al* has divided the compensation technique in several steps –

1. **Problem Avoidance - Design for Control** : decreasing the mass of the mechanical system, increasing damping by using proper lubricant or sliding surfaces like bearing or by coating or lining the surfaces, increasing the stiffness by changing geometry and composition of the bulk material and decreasing inertia though decreasing inertia is not always practical. Designing for control does not guarantee the passive elimination of stick-slip, it usually produces a system which is easier to control and which possesses better performance characteristics.

2. **Non-model based compensation for friction :**
   a) ***Stiff PD control :*** Stick slip can be eliminated through either high derivative (velocity) or high proportional (position) feedback. They are best used together as they are complementary. While derivative feedback is additive with inherent system

damping, this is not the case with proportional feedback. System stiffness acts in series with controller stiffness. Thus, high gain proportional control is most successful in systems which can be designed for high rigidity.

b) ***Integral control :*** Integral control of position or velocity is almost always introduced to minimize steady-state errors. Integral action causes limit cycle when tracking at low or zero velocities. To overcome limit cycling, one standard technique is to employ a deadband as the input to the integrator block. This imposes its own steady-state error which is hoped to be less than that before the integral action was added. Integral control is also ineffective at velocity reversals. Integral windup from prior motion can inhibit breakway. To prevent this, the integral term is typically reset at velocity reversals. But this causes insufficient action from the integral controller to overcome stiction.

c) ***Dither :*** Dither is a high frequency zero mean signal introduced into a system to modify its behavior. Amplitude of the Dither should be so high that the stiction is overcome and the frequency should be high enough, so that generated disturbances is above the interesting frequency range of the system [4]. Dither can stabilize unstable systems and is used to improve performance by modifying nonlinearities in adaptive control. By applying a dither of amplitude α and frequency ω to the discontinuous function y(t) = sgn(u(t)), can be averaged to a continuous function.

d) ***Impulsive Control :*** Impulsive control is distinguished from dither in that no compensation signal is added to the control signal, but the control signal itself is generated as a sequence of pulses. The pulses should be so large that they overcome the stiction level [4]. The impulses used are not zero mean and must be calibrated to produce desired result.

e) ***Joint Torque Control :*** It is a sensor-based technique which encloses the actuator-transmission subsystem in feedback loop to make it behave more nearly as an ideal torque source. Disturbances due to undesirable actuator characteristics or transmission behaviors can be significantly reduced by sensing and high gain feedback.

f) **Dual mode control :** In this approach two markedly different mechanism dynamics – a) Macro-dynamics, the ordinary dynamics of the mechanism and b) Micro-dynamics, which governs motions that depend upon elastic deformation in the frictional contact. Since, the dynamics are drastically different, two different controller structures are required and hence it is called dual mode control.

3. **Model based compensation for friction :**
    a) ***Fixed compensation :*** When a model of friction is available, it is possible to compensate for friction by applying a force /torque command equal and opposite to the instantaneous friction force. This presumes that force or torque actuation of adequate bandwidth is available and is stiffy coupled to the friction element.

    b) ***Friction identification and adaptive control :*** The friction parameters may be determined either offline, following a data gathering experiment, or continuously on-line as part of operation of the machine. Then these auto-updated parameters are used in the model based friction compensation.

2.5 Compensation of Stiction in Process Control

Since more than 90% of the industrial valves are pneumatic [4] and pneumatic valves exhibit slower dynamics than servo-systems, compensation techniques reported by Armstrong-Helouvry *et al* [13] cannot be directly applied to process control loops [3]. Kayihan and Doyle and Hagglund have addressed stiction compensation algorithms for pneumatic control valves. The approach of Kayihan and Doyle requires a valve model with valve parameters such as stem mass, stem length, etc. The process model should also be known as priori. Obtaining such detailed valve and model information for several hundred valves is a practical limitation [3, 14].

Though Dither and Impulsive control are well established in servo-system, it is not possible to move the pneumatic valve with a high-frequency input signal, and it is therefore impossible to avoid stick-slip motion. However, a faster transition between the different stiction positions can be obtained. This higher frequency of the oscillations may improve the control significantly [4].

Determination of the exact location for applying stiction compensation method is another problem with the previous two methods. There are several so called smart positioners available, and it is sometimes suggested that stiction compensation should be performed on them. The positioners measure and control the valve stem position, not the valve position. The problem is, that the stem position may not reveal the correct information about the valve position. Because of the elasticity of the valve stem, the valve may very well be stuck even though the stem moves. This is a problem especially in rotary valves. The conclusion is that to really control the valve position it is necessary to measure the flow through the valve. This fact makes the controller the best candidate for valve supervision and stiction compensation, since the controller takes the flow, perhaps smoothed out, as input signal [4].

2.5.1 The Knocker Method

To avoid the problem with positioner discussed in the previous sub-section, Hagglund [4] proposed a new compensation technique for pneumatic valves called the knocker. In this technique, short pulses of equal amplitude and duration in the direction of the rate of change of the control signal is added to the control signal. The basis level for the pulses will gradually change as long as the control error is non-zero with the help of an integrator in the controller. This means the pressure drop over the actuator piston will increase gradually until the valve slips.

It is possible that there will be several pulses of wrong sign shortly after the slip since the measurement signal will not react to the slip immediately, and therefore not the control signal either. However, these extra pulses will not do any harm, since the valve is stuck at a new position where the pulses cannot overcome the stiction level.

This is the advantage of having small energy content in each pulse.

Figure 2.4 shows the block diagram of a knocker that is used in a feedback control loop. Here , input to the process will be summation of the output from the controller(u_c) and output from the knocker (u_k).

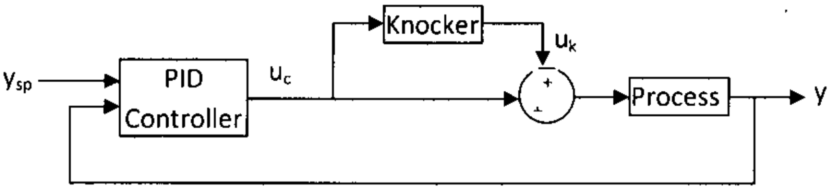


***Figure 2.4**. Block diagram of knocker in a feedback loop.*

Output from the knocker is a pulse sequence that characterized by – 1) the pulse amplitude a, 2) the pulse width τ and 3) the time between each pulse h_k. Here, the controller sampling period is h. Output from the knocker can be mathematically as follows :

$$u_k(t) = \begin{cases} a\,\mathrm{sign}(u_c(t) - u_c(t_p)), & t \le t_p + h_k + \tau \\ 0 & , t > t_p + h_k + \tau \end{cases} \qquad \text{.......................................} \quad (2.1)$$

where, t_p is the time of onset of the previous pulse. So, the sign of each pulse is determined by the rate of change of control signal $u_c(t)$.

Choice of knocker parameter is of immense importance. According to Hagglund [4], the transfer function between the knocker output ($u_k(t)$) and process output, y is -

$$Y = \frac{G_P}{1+G_pG_C} U_k \qquad \text{...(2.2)}$$

$G_p$is process transfer function and G_C is controller transfer function. Since, $u_k(t)$ is a pulse with amplitude (a) and width (τ), the process output becomes –

$$Y = \frac{G_P}{1+G_pG_C}(1 - e^{-s\tau})\frac{a}{s} = \frac{G_P}{1+G_pG_C}\, a\tau \qquad \text{.......................................(2.3)}$$

This means the product $a\tau$ determines the energy of each pulse in the knocker. Too large amplitude results uncontrolled opening of the valve. So, it is desirable to keep a relatively small a. The field tests performed by [4] suggests that it is suitable to choose a between the interval 1% - 4%. Generally a is fixed once and for all. Whereas, τ can be varied. It should not be too small because in that case too much energy will be feed at the moment the valve slips. Generally it is an integer multiple of the controller sampling interval (h). The knocker sampling interval (hk) will be multiple of knocker pulse width, τ.

So, in a nutshell according to [4]

$$\begin{aligned} &1\% < a < 4\% \\ &\tau = n^{*}h \text{ [here, n = 1 to 2]} \qquad \text{...(2.4)} \\ &h_k = m^{*}\tau \text{ [here, m = 2 to 5]} \end{aligned}$$

A field test with a pure PI flow controller (Controller gain =1, integral time constant = 5s and Controller sampling interval(h) = 0.2s and a first order low pass filter with time constant 5s) and knocker setting as a = 3%, τ = 2h = 0.4s, and h_k = 2.5τ = 1s shows that IAE decreased 55% and ISE decreased to 31%.

The field test shows that the knocker reduces the oscillation amplitude in the cost of oscillation frequency. The oscillation period obtained using the knocker is about 1/3 of the period obtained using the pure PI controller.

A second run of the experiment was performed to check the effect of large h_k [4]. here the knocker setting was a = 3%, τ = h = 0.2s, and h_k = 20τ = 4s. Since the sampling period is high, control signal u_c will build up almost the pressure that is needed to generate a slip of the valve. When the pulse is applied, the pressure drop over the valve piston will be much larger than needed to overcome the stiction. The result is an oscillation that is significantly larger than what is obtained using the pure PI control.

Another observation of Hagglund [4] is that since flow controllers are often used in secondary loops in cascade control, stick-slip motion in these inner loops forms oscillating load disturbances on the primary control loop. By increasing the frequency of these oscillations, their effect on the primary controller will be smaller, since the primary control loop has a lower bandwidth and therefore attenuates higher frequencies more than lower.

The friction compensator by [4] is also implemented in industrial controllers and DCS manufactured by ABB, this means knocker can compensate stiction quite efficiently.

Though Hagglund [4] assumed that there might not be significant wear on the valve due to knocker technique, in a study of the performance of knocker [3] it is observed there is significant valve movement with possibility of wearing when the knocker algorithm was implemented on pneumatic valve. In this study [3], it is also found that the choice of knocker parameters influences its performance. Experimental and simulation case studies were demonstrated as proofs of the study. The sensitivity analysis of the knocker parameters in compensating stiction of a CSTR and the liquid level system shows that the knocker provided economically beneficial performance (i.e. small pulse amplitude and low pulse energy) around the region when the pulse amplitude was selected about half of the stiction measure, the pulse width was about twice the system sampling time and the knocker time interval was 4-6 times of the system sampling time. Also a framework that integrates stiction estimation procedure for effective compensation is proposed [3]. Upon implementing the proposed framework on a level loop shows reduction in measurement variability of 6-7 times.

2.5.2 Improvements of Knocker Method

It is observed that the reduction at the output variability was achieved at the cost of an aggressive stem movement. Such an aggressive stem movement is not preferred as it may wear the valve quickly. Hence, a design strategy for compensating stiction should ideally meet the following requirements:

a) Less aggressive stem movement (or valve movement)
b) Reduced Output variability
c) Less energy in the signal that is added to the control signal.

A novel design strategy that attempts to meet these requirements is proposed by [5]. The proposed method is devised based on the physical model of the stiction phenomenon and uses the stiction severity.

Here, an optimization formulation that minimizes the objective function J over a defined prediction horizon is posed for designing the compensator signal (F_k).

$$\min_{F_k}(OF) = \lambda_1 ISE_Y + \lambda_2 Var(X) + \lambda_3\, \phi(X) \quad \text{..(5)}$$

The first term in the objective function (OF) is the integral square error (*ISE_Y*) of PV (with respect to set point), the second term addresses the valve stem variability *Var*(*X*), and the third term includes valve aggressiveness ($\phi(X)$). F and X are vectors obtained over a defined prediction horizon (p). λ_1, λ_2 *and* λ_3 represent either the cost associated for maintaining the product quality or the penalty for each term in OF. A compensating signal that minimizes OF is the best possible signal that will meet the requirements of an ideal compensator. However, formulating such an objective function requires several assumptions to be made. These assumptions are listed below:

1. The plant model (G_P) is available.
2. The controller (G_C) structure and its parameters are available..
3. Stiction is already detected.
4. Stiction severity measure *d* is ascertained *a priori.*

Two simulations were performed to highlight the usefulness of the optimization approach [5]. The optimization approach used the 'fmincon' algorithm of the MATLAB optimization toolbox used. It was seen that the optimization approach has parameters that need to be tuned to attain efficient stiction compensation. Two main drawbacks are seen with the optimization approach:

a) As the objective function is non-smooth, the optimizer was not able to attain the global minimum; instead a local solution was obtained. This is evident from Figure 2.5, where for both runs, the process output failed to reach the set-point. This is because the stem position did not move to the correct steady state value, instead moved the stem close to it with an offset. Also the objective function values obtained for the various compensating signals (simulated as a grid of values for the next two moves) showed that the objective function is generally non-smooth but convex.

b) When the optimization approach was tried on an experimental level system at Clarkson University, the Simulink interface could not solve the optimization formulation between two successive iterations, due to real-time issues. Alternate non-gradient based optimization techniques that use function evaluation such as DIRECT (DIvide RECTangle method), Implicit iteration can be studied to overcome the real-time issues.

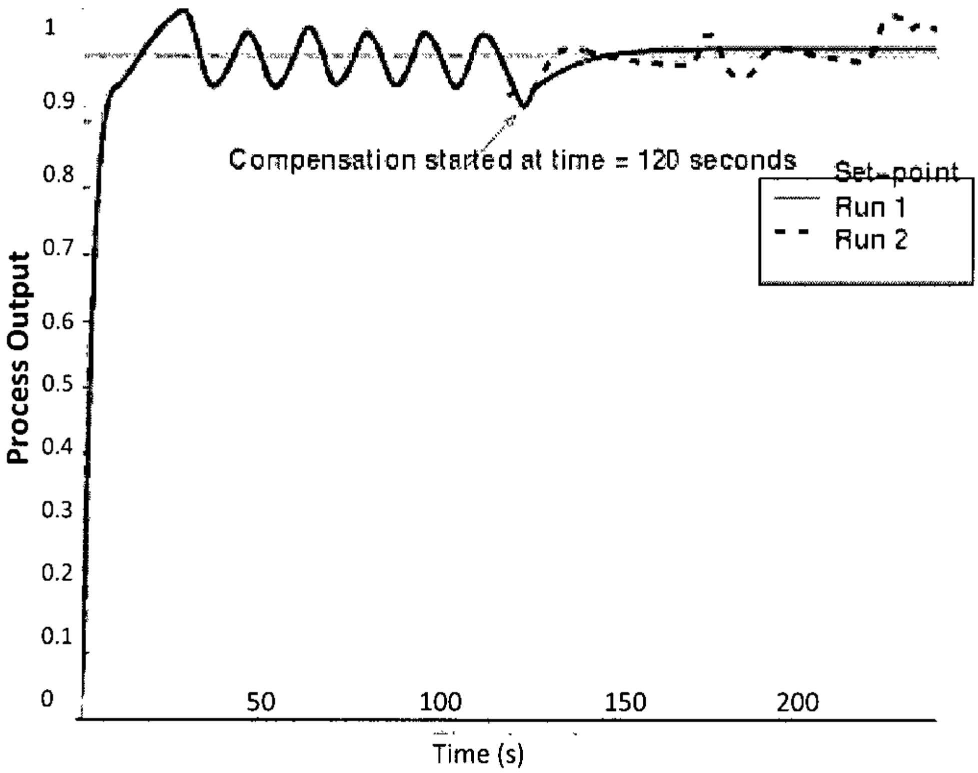


Figure 2.5. Results for optimization approach for compensation, (a) Process output and (b) Controller output. The compensation started at time 120 seconds.

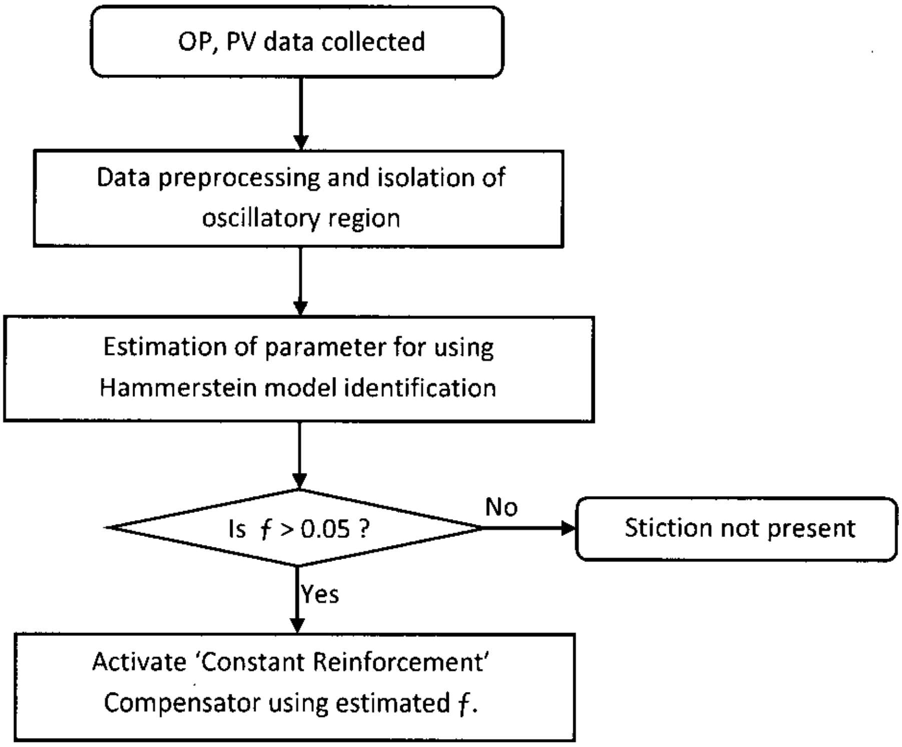


Figure 2.6. Unified framework for stiction diagnosis and compensation.

It is seen that based on the penalty imposed for each term in the objective function, the duration for the process output to reach its set-point varies. Also, the amount of variability and stem friendliness factor varies based on the weights of λ. Though, preliminary studies suggest that the model based compensation method can be a useful strategy for stiction compensation. Further analysis of the effect of model plant mismatch, incorrect stiction measure, real time issues on the proposed stiction compensation approach needs to be done before these methods can be implemented online.

Ivan *et al* [15] presents a unified approach for stiction quantification and compensation. The block diagram of this approach is shown by Figure 2.6.

Here, f is a friction parameter which is assumed to be equal to both static and kinetic friction. When the static friction f will be overcome, a residual force equal to it will be present. So, the valve stem will always be in moving condition until the valve input change its direction because static friction will always be overcome. However, the authors [15] suggested an improved version of knocker, by adding constant amplitude to the OP signal will be done (Figure 2.7).

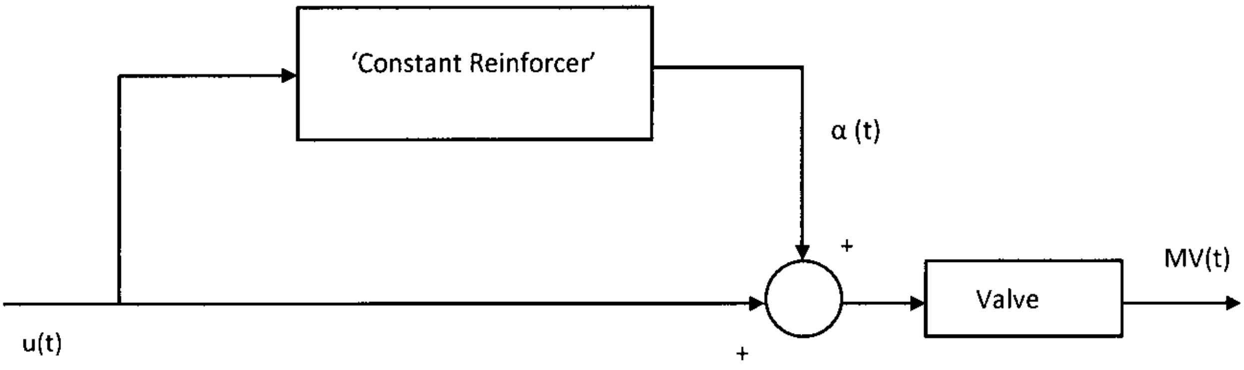


Figure 2.7. *Block diagram for CR approach*

Here, $\alpha(t) = a\ \mathrm{sign}(\Delta u)$ is added to u(t). Since, in this method a constant reinforcement is provided to the OP signal, the author has termed it as Constant Reinforcement or CR method. The authors have performed simulation by using the stiction model of Choudhury *et al* [16] and found that much lower variability in PV is achieved at the expense of greater frequency (Figure 2.8) of the valve stem oscillation, which might cause severe wearing of valve.

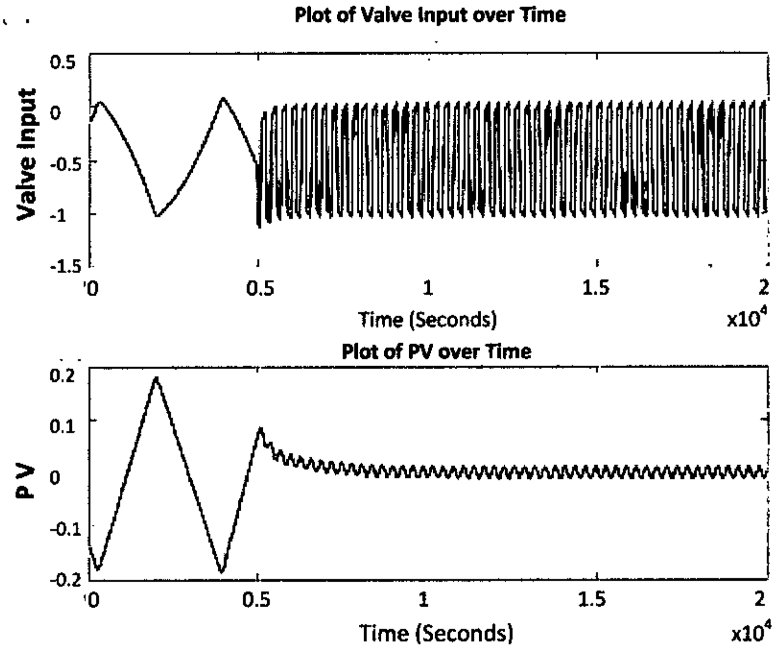


Figure 2.8. Plot of valve input and PV over time for (c) level control system (weak stiction).The compensator kicks in at time 5000 s.

2.5.3 Two Move Method

Another alternative approach of Knocker is the two move method proposed by [6]. It is based on one parameter stiction model. The one parameter stiction [2,3,5,6] model is given as below:

$$x(t) = \begin{cases} x(t-1)\ if\ |u(t) - x(t-1)| \le d \\ u(t) \quad otherwise \end{cases} \quad \text{..........................}(2.6)$$

Here x(t) and x(t-1) are the present and past stem movements, u(t) is the present controller output and d is the valve stiction band.

The structure of the two move compensator is shown in Figure – 2.9. The compensating signal (f_k) is added to the controller output signal(u_c) as seen in the figure.

$$f_k(t) = u_c(t) + sign\left(\frac{du_c(t)}{dt}\right) f_k(t) \quad \text{..........................}(2.7)$$

This signal can assume two values causing two movements of the valve stem. The first signal moves the stem from its sticky position and it is given as follows:

$$f_k(t) = |u_c(t)| + \alpha d, \quad \text{..........................}(2.8)$$

where d = stick band and α is a real number greater than 1

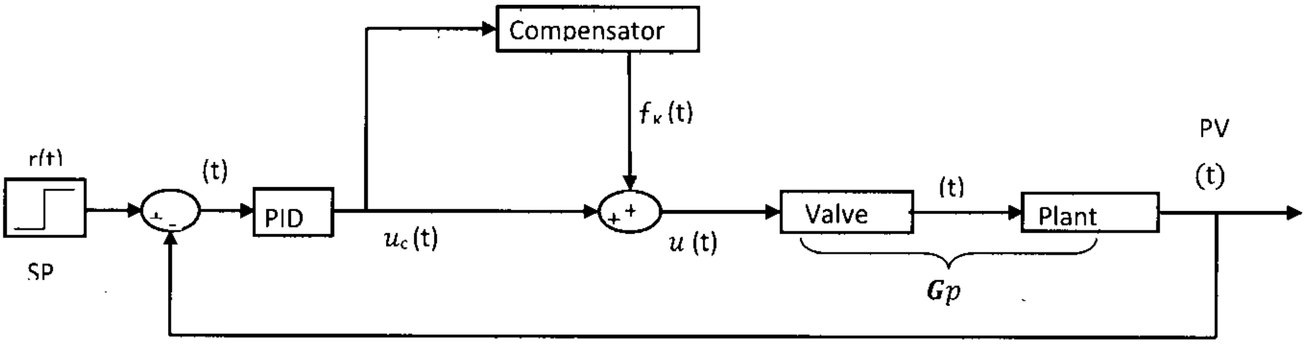


Figure 2.9. *Structure of the two move compensator.*

During this move we just have to be careful that it does not reach the saturation point of the stem. Then, the second move will take the stem to its steady-state position and it is given by as follows -

$$f_k(t+1) = -u_c(t+1) \quad \text{.......................................(2.9)}$$

It is interesting to observe that after the second movement, the stem does not move from this steady-state position since the controller output is cancelled by the action of these two movements [17]. And then the signal remains constant. Advantages of the two move method are – a) Process model and controller models are not strictly required, b) it can also accommodate some degree of uncertainty in the stiction band, c) from the experimental demonstration it is also visible that it can work under more realistic situation also [6].

It is noted that set-point change or disturbances are not allowed during this compensation effect. This method relies on two assumptions – a) the process measurements are represented by deviation variables and b) the steady-state value of valve position is known. The second assumption is rarely true [17]. Another disadvantage is that after the stem has reached to its steady-state position, the minimum time needed for the process to track the set-point will be at least the settling time of the process [6].

2.5.4 Improvements of Two Move Method

Since the application of the two-move method requires the knowledge of OP_{ss}, [17] have proposed improvements in order to estimate the joint process and valve gain to calculate the value of OP_{ss}. Four movements which are given by Equation (2.10), are applied in open loop.

$$u_i(t) = \begin{cases} \alpha_1; & t_1 < t \leq t_1 + T_m \\ u_i(t_1) - sign(\alpha_1)\alpha_2; & t_1 + T_m < t \leq t_1 + 2T_m \\ u_i(t_1 + T_m) - sign(\alpha_1)\alpha_3; & t_1 + 2T_m < t \leq t_1 + 3T_m \\ u_i(t_1 + 2T_m) - sign(\alpha_1)\frac{SP - y_t}{k_P}; & t > t_1 + 3 \end{cases} \quad \text{.........................(2.10)}$$

here, α_1 = *sign* $\left(\frac{du_{cf}(t_1)}{dt}\right)$ *(S +2J+| $u_c(t_1)$ |), $u_{cf}(t)$ =filtered signal from controller output, T_m is the time interval required for the stabilization of the PV, SP = Set Point, k_p = joint process and valve gain =* $\frac{\Delta y}{\alpha_3}$*, S = Deadband + Stick band, J = Slip-jump.*

In the first movement the stem moves from its sticky position. The second movement is necessary to change the direction of the valve movement. The third movement has the same direction of the second and it is used to estimate the gain of Valve and Process jointly. This is possible because in this movement the direction has not been changed and is not affected by dead-band. The fourth movement targets to bring the valve stem to its desired steady state position. This is done using the gain estimated in the previous movement and keeping the direction unchanged [17].

In this improved method the input of the valve is switched between the output of the PID controller and the compensator, as shown in Figure 2.10. It is assumed that the PID controller is able to handle disturbances and set point changes even in the presence of stiction though oscillating behavior might be introduced. When compensator is switched on, PID controller tracks the tracking signal and the control error. If the compensator succeeds, the control error tends to zero and the output of the PID tends to compensator output.

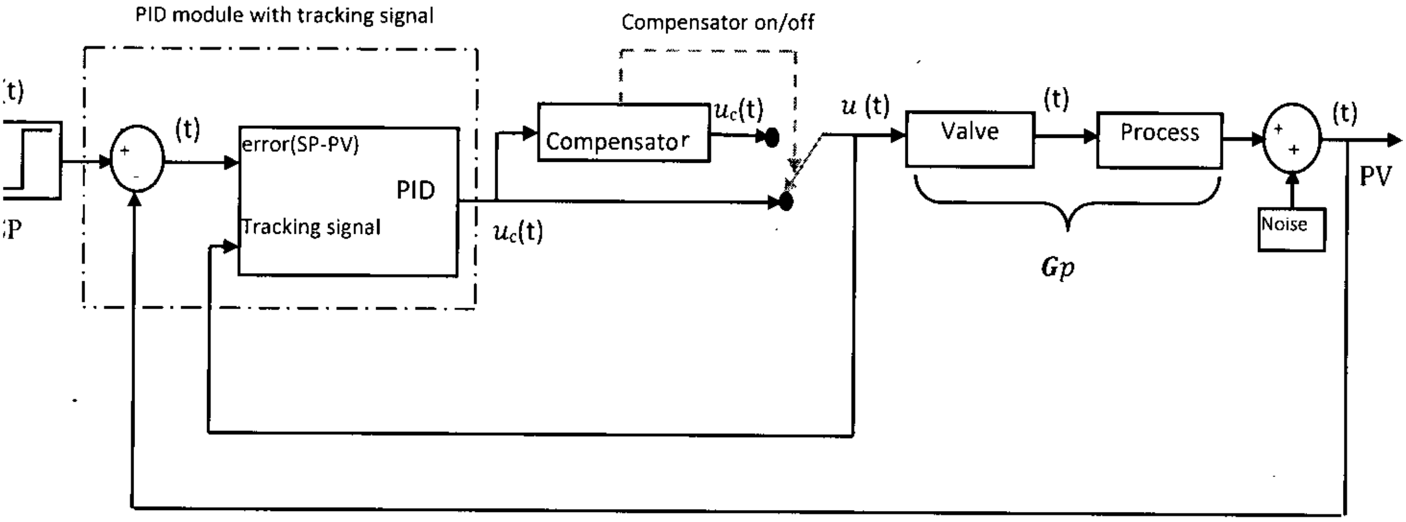


Figure 2.10. *Structure of the improved two move and four move compensator.*

"Using the amplitude of OP as an approximation of S, and considering that J is in general a small fraction of S, all required information for compensation comes from the proposed algorithm. The values of α_i, i=1, 2, 3, 4 are not critical and should only be big enough to ensure the valve movements. The great disadvantage of the proposed method is its dependence on open loop movements, which makes it susceptible to disturbances that can happen during the

time interval from t_1 to t_1+4T_m. In this case, the compensation steps should be restarted", and this method is only applicable to self-regulating processes only [17].

Another method that needs only two movements and do not require the knowledge of OPss are proposed in [17]. In this method, again the compensating signal is not added to the output of the PID (Figure 2.10). This method ensures that the valve moves smoothly until the error (SP-PV) is around zero. At this instant, a signal contrary to valve motion is applied to keep the error near about zero [17].

The limit cycle produced by stiction in the OP-PV plot is shown by the sequence of points (A, B, C, D) in Figure 2.11. The sequence of movements if the proposed method (E, F, G, H, I, J, K) is also shown in the same figure.

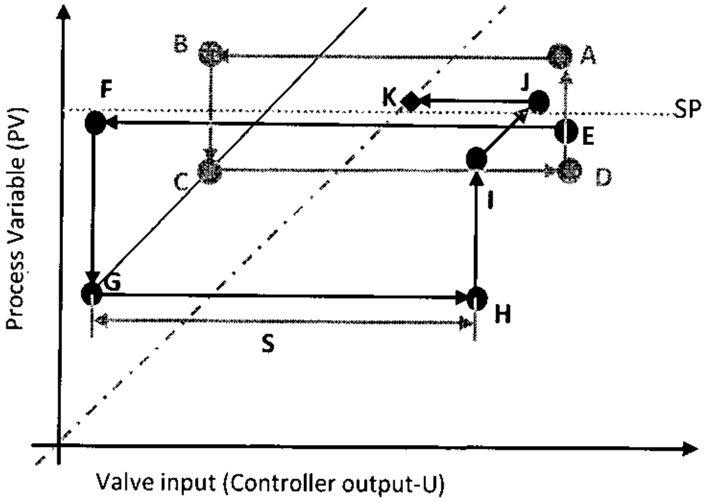


***Figure 2.11.** Behavior of the Compensating Signal $u_i(t)$*

The compensation signal $u_i(t)$ necessary to produce the behavior shown in Figure 2.11 is given by :

$$u_i(t) = \begin{cases} u_c(t_1) + \alpha S\left(1 - \frac{t-t_1}{kT_p}\right)\text{sign}\left(\frac{du_{cf}}{dt}\right); & t_1 \le t < t_2 \\ u_c(t_1) + \frac{\alpha S}{2}\text{sign}\left(\frac{du_{cf}}{dt}\right); & t \ge t_2 \end{cases} \qquad \text{.................................(2.11)}$$

here, u_c is the controller output, u_{cf} is the filtered controller output,T_p is the period of Oscillation, α is a real number greater than 1, S is the Dead band plus Stick band and t_1, t_2 and k are parameters presented with the algorithm.

Both simulation and pilot plant experimental experience (Figure 2.12) shows that this modified two move method algorithm treats equally the set point changes and perturbations. If error is introduced the compensation restarts and reduces the error. But where set point or perturbation changes continuously e.g. control loops in cascade configuration, the proposed method may present poor performance. This method can be applied only to self-regulating processes and it also requires that the process and control valve have similar dynamics [17].

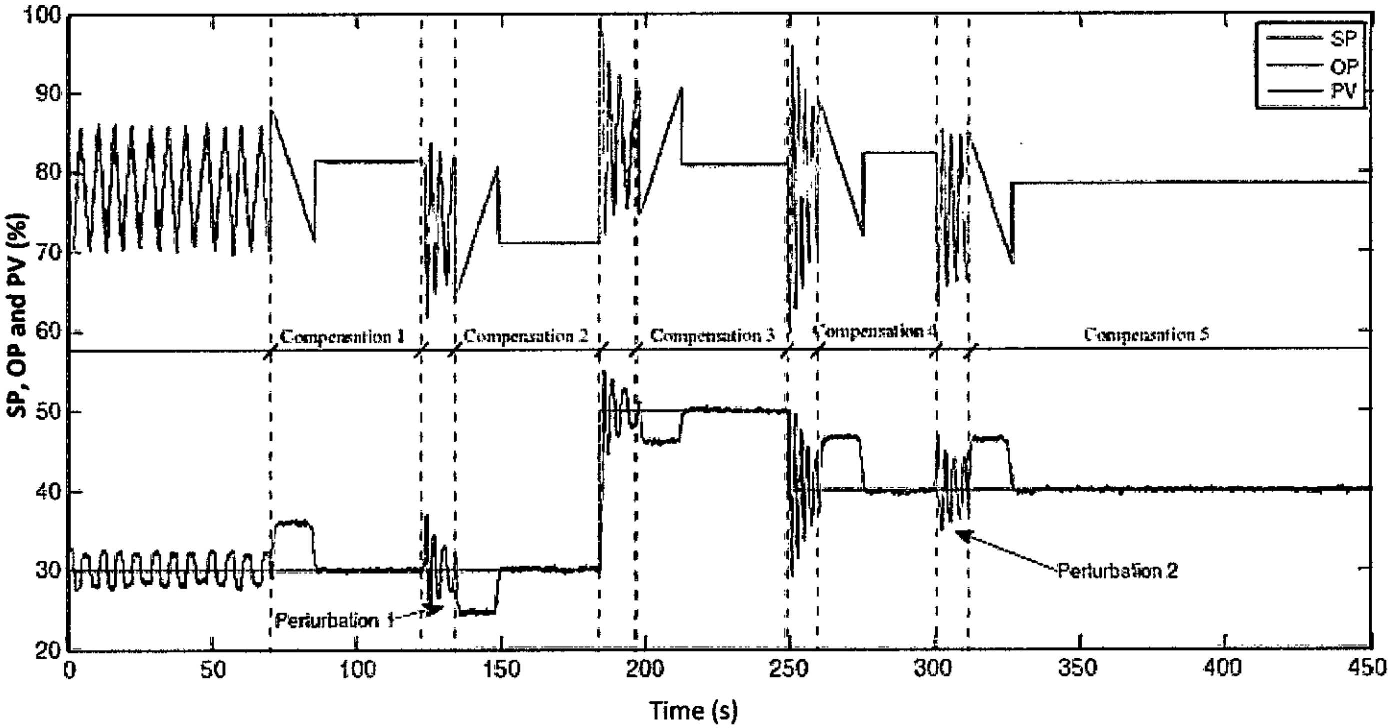


Figure 2.12. Stiction compensation by the proposed compensator in a pilot plant flow control loop.

2.6 Conclusion

In this chapter, definition of stiction is discussed from different point of view. Also, the possible physical causes of stiction were depicted. The available techniques of stiction compensation are also discussed. There are two methods of compensation till present –

1) **Knocker** proposed by Hagglund [4*]* and

2) **Two move method** by [6].

But only the knocker method has got popularity and stability. In this study, it was tried to develop a new method of compensation by efficient tuning of the existing PID controller itself, since a PID controller is a compulsory part of the control system. So, it will not take any extra cost. Again, an inverse stiction method has been attempted to compensate stiction. Simulation results are also observed and it is found from the simulations that the inverse stiction method works well both in parallel and series combination.

Chapter 3

Efficient Tuning of PID controller for Compensating Valve Stiction

3.1 Effect of PID Controller Tuning on Valve Stiction

The existing methods of compensation of control valve stiction are as follows-

- Addition of an extra signal in the form of Knocker
- A compensator for two move or improved two move methods

There is no noticeable work with a simple PID controller on stiction. Since PID controller is available with every automatic control system, it was tried to develop a method by using PID or a formatted version of PID controller to compensate stiction.

3.1.1 Integral Part should be avoided

In this study, a Second Order Process with Time Delay (SOPTD) was chosen. The reason for choosing a SOPTD process is that this type of process shows a sustained oscillation in presence of stiction. So, study with this type of process will be helpful to understand the effect of compensating method on stiction in a better way. Here, the process was chosen as follows :

$$G(s) = \frac{3e^{-5s}}{(5s+1)(10s+1)} \dots\dots\dots\dots\dots\dots (3.1)$$

The Internal Model Controller (IMC) settings for this SOPTD process can be calculated as follows: $K_C = 0.6, \tau_I = 15, \tau_D = 3.33 \dots\dots\dots\dots\dots\dots (3.2)$

In this case, the two parameter Stiction model of Choudhury [16] was used for simulating Stiction. 'SIMULINK' toolbox of 'MATLAB' software was used to perform the simulations using different controller settings. Figure 3.1 shows the SIMULINK block diagram that was used to compare the effects of different combination of controllers such as Proportional (P), Proportional Integral (PI), Integral (I), Proportional Derivation (PD) and Proportional Integral Derivative (PID).

In this block diagram, seven different combinations of controllers were used. 'SWITCH' counter was used to change the controller combinations after a fixed time period. In the first 1000s there was no controller in the closed loop system. But since it is a closed loop system, it itself acts as a proportional controller with Kc = 1. Then, Switch counter will activate a Proportional only controller with Kc = 0.6 (as determined by the IMC method) for the next 1000s. After 2000s, a PD controller with Kc = 0.06 and D = 2 (since, $\tau_D = 3.33s$ as determined by the IMC controller settings) was activated. After 3000s, an Integral only controller will be activated with I = 0.04 (since, $\tau_I = 15$ as determined by the IMC controller settings). For the next 1000s, a PI controller with P = 0.6 and I = 0.04 was activated. For 5000-6000s a PID controller with the IMC settings was activated. For the last 1000 second again a PD controller was activated with derivative part 5 times higher than the IMC setting. Set point was changed from 4mA to 6 mA after 300s. The controller parameters are listed in Table 3.1.

***Table 3.1** : Controller parameters for simulating the control loop as shown by Figure 3.1*

Time	Proportional part, Kc	Derivative part, τ_D	Integral Part, τ_I
0-1000s	1	-	-
1000-2000s	0.6	-	-
2000-3000s	0.6	3.33s	-
3000-4000s	-	-	15s
4000-5000s	0.6	-	15s
5000-6000s	0.6	3.33s	15s
6000-7000s	0.6	16.65s	-

A filtered random number was also added with the output as a source of disturbance. The filter was a first order transfer function with gain = 1 and time constant = 2. The total simulation period was 7000s. Here, the effect of stiction was observed in case of a unit step change. The sampling period was set to 1s.

Figure 3.2 shows the response of the closed loop simulation of the controller combinations of Figure 3.1. From this figure, it is seen that there is existence of limit cycle in the loop whether a controller is used or not. For time 0-1000s, when there was explicitly no controller (though Kc =1, since a closed loop cycle itself acts as a Proportional Controller of gain 1) still limit cycle of average amplitude 4 was seen. For time 1000-3000s, about 50% reduction of the limit cycle amplitude is seen. Note that, in the first 1000s of this 2000s a Proportional only controller was used and in the next 1000s a PD controller was used. For time 3000-4000s when an Integral

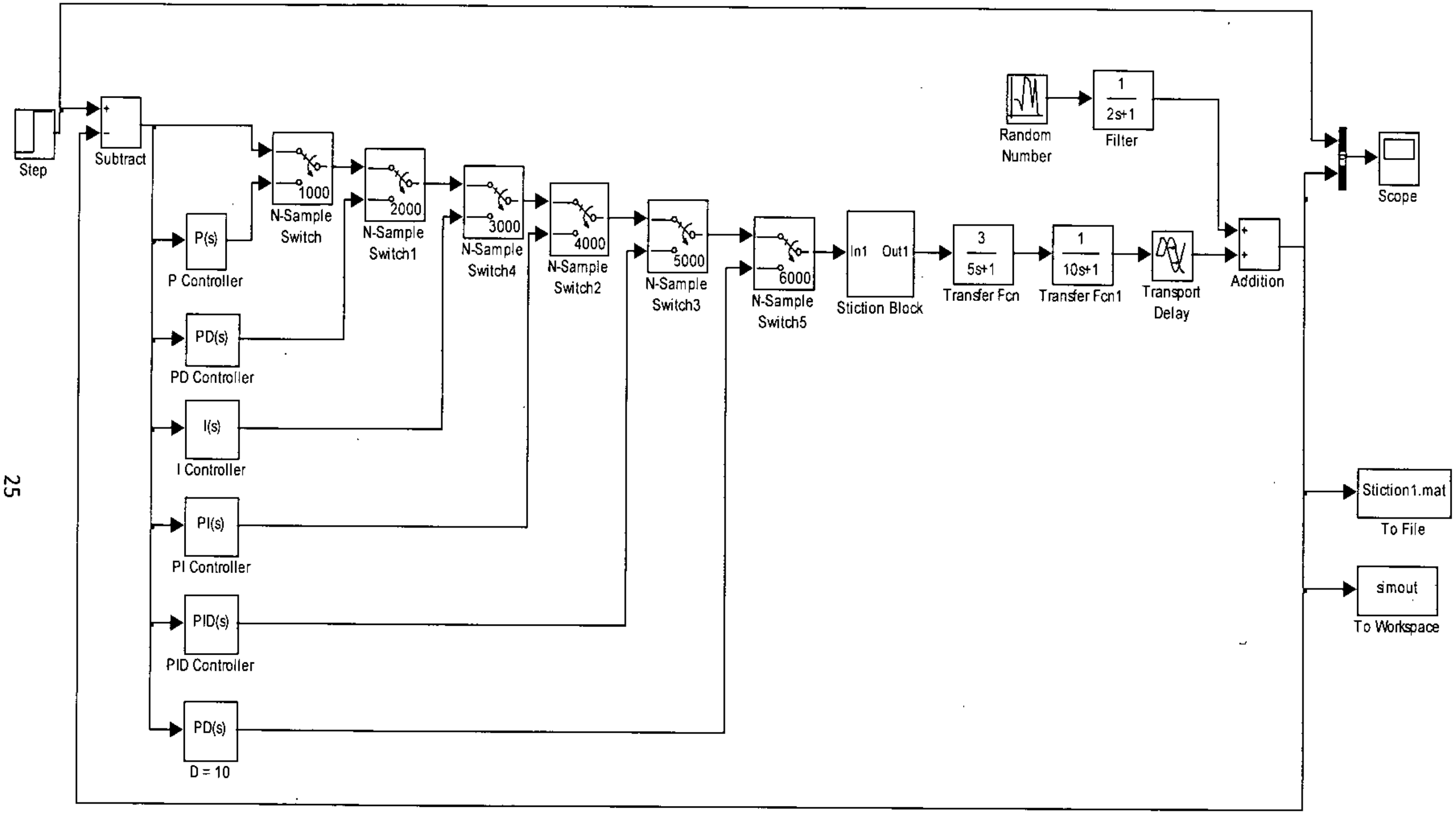


Figure 3.1. A closed loop block diagram to compare the effects of different combinations of PID Controller on Stiction. For time, a) 0-1000s a P Controller with Kc = 1, b) 1000-2000s a P Controller with Kc = 0.6(Calculated by IMC method), c) 2000-3000s a PD controller with Kc = 0.6 and $\tau_D = 3.33$s(as IMC), d) 3000-4000s an Integral Controller with $\tau_I = 15$s, e) 4000-5000s a PI Controller with P=0.6 and $\tau_I = 15$s, f) 5000-6000s a PID Controller with P=0.6, $\tau_I = 15$s and $\tau_D = 3.33$s and g) 6000-7000s a PD controller with Kc = 0.6 and $\tau_D = 16.65$s (Derivative part is 5 times higher than IMC) was activated.

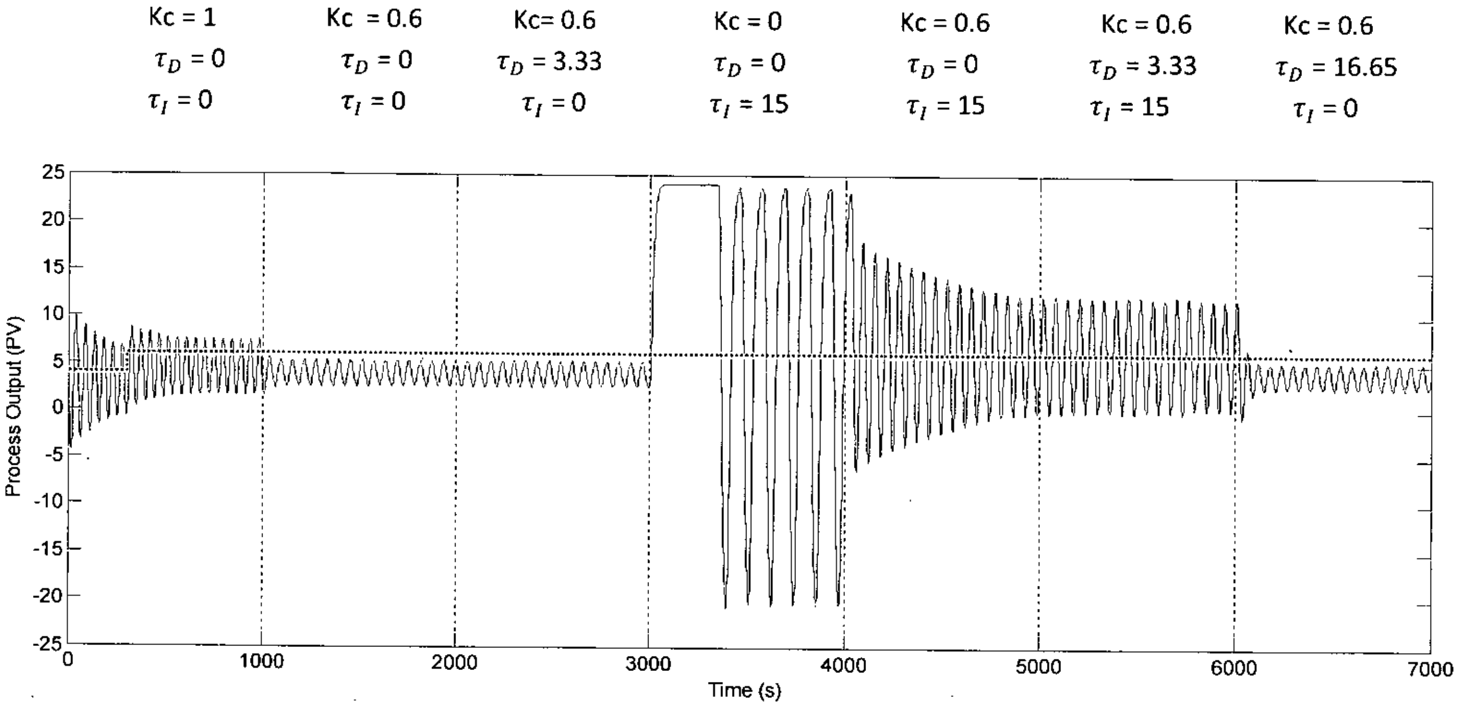


Figure 3.2. The response of the simulated closed loop block with seven different controller combinations as shown in Figure 3.1. The dotted line indicates the desired process output(setpoint) and solid line indicates the simulated process output.

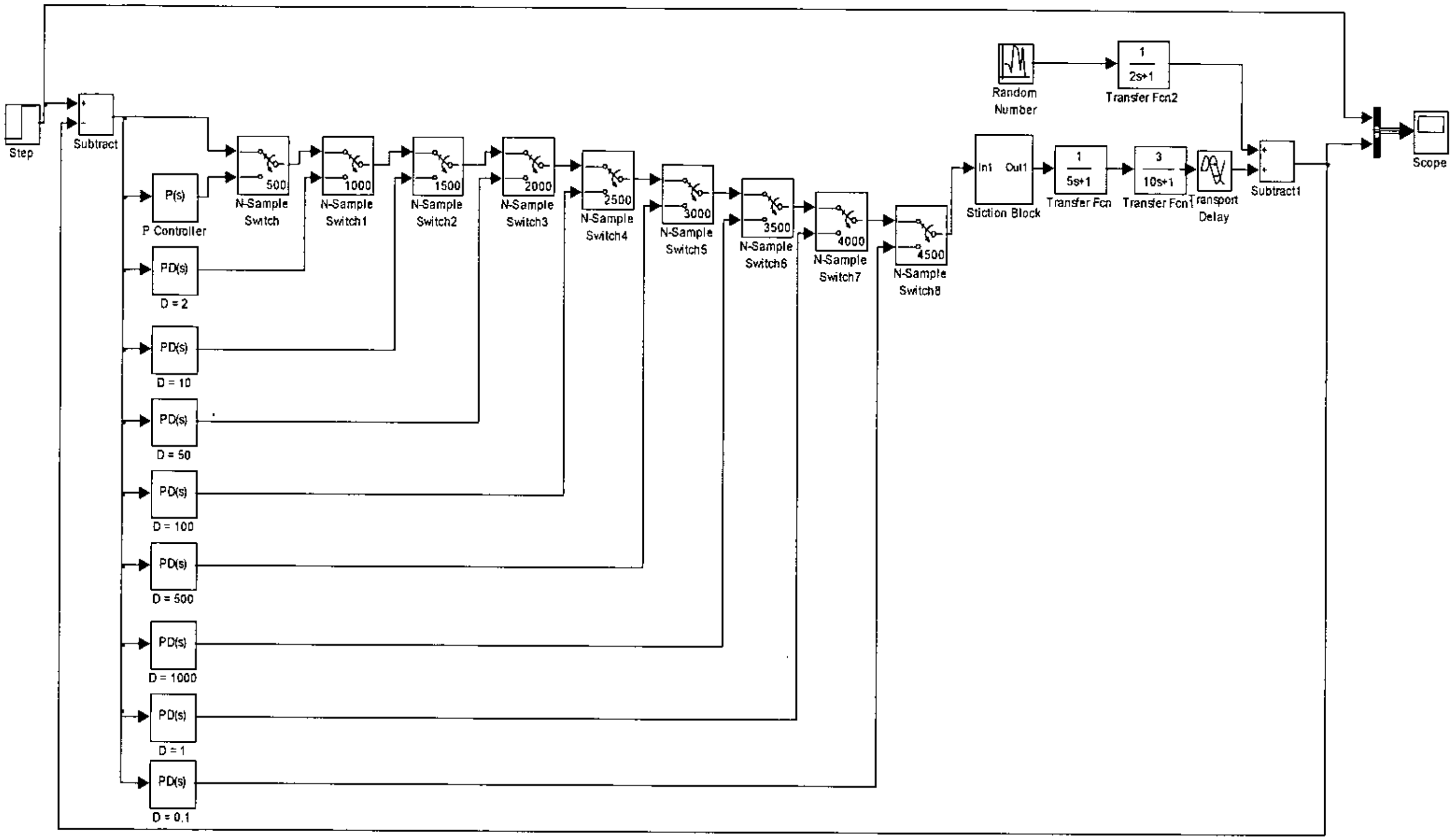


Figure 3.3. A Closed Loop block diagram to compare the effects of different PD Controllers on Stiction. For time, a) 0-500s a P Controller with Kc = 1, b) 500-1000s a P Controller with Kc = 0.6(Calculated by IMC method), c) 1000-1500s a PD controller with Kc = 0.6 and D = 2 (as IMC τ_D = 3.33s), d) 1500-2000s a PD controller with Kc = 0.6 and D = 10, e) 2000-2500s a PD controller with Kc = 0.6 and D = 50, f) 2500-3000s a PD controller with Kc = 0.6 and D = 100, g) 3000-3500s a PD controller with Kc = 0.6 and D = 500, h) 3500-4000s a PD controller with Kc = 0.6 and D = 1000, i) 4000-4500s a PD controller with Kc = 0.6 and D = 1 and j) 4500-5000s a PD controller with Kc = 0.6 and D = 0.1 was activated.

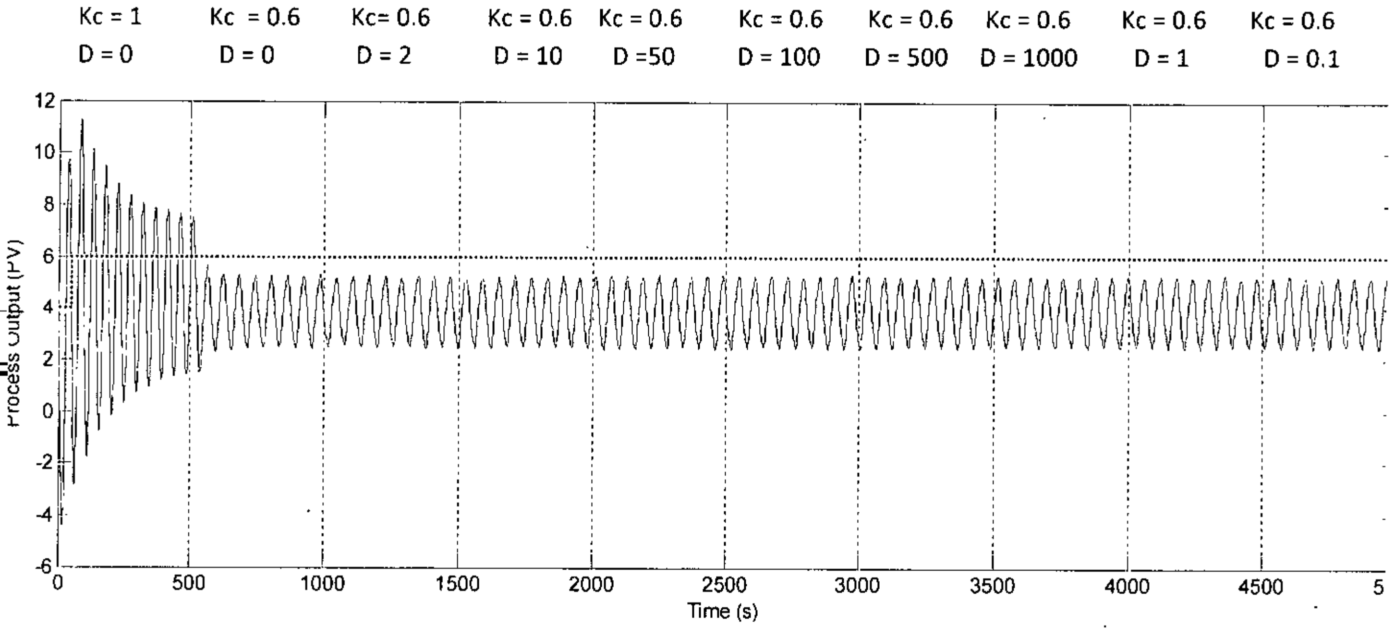


Figure 3.4. The response of the simulated closed loop block with ten different P or PD controller combinations as shown in Figure 3.3. The dotted line indicates the desired process output(setpoint) and solid line indicates the simulated process output. Setpoint was changed from 4 mA to 6 mA after 50 seconds.

Controller was used; an increase of about 600% in the limit cycle was seen. For time 4000-5000s, a PI Controller was used. Still a limit cycle of 300% to 200% was seen. For time 5000-6000s, when PID Controller was used an average limit cycle of 200% was seen. For time 6000-7000s, when again a PD controller with a Derivative part of 5 times higher than IMC, again a 50% reduction was seen.

So, from this simulation, it can be concluded that an Integral part is not at all suitable for handling Valve Stiction which completely complies with the study of [7]. It is clearly evident that P and PD controllers have shown positive effects to handle valve stiction. In the later sections of this study, detailed examinations on P and PD controllers will be performed.

3.1.2 Effect of Derivative Part of PID Controller on Stiction

In the previous section, it is seen that the Integral part rather worsens the process response in presence of a Sticky problem, whereas P and PD controllers have shown positive effects.

Figure 3.3 shows the block-diagram of the SIMULINK model by which effect of ten different Proportional only and PD controllers on Stiction was studied on the same process as given by equation 3.1. In the first 500s, only a Proportional controller was activated with Kc = 1. For 500-1000s a proportional only controller with Kc = 0.6 was activated as given by the IMC method. In the next six cases, eight different PD controller was activated in which the proportional part was kept fixed to its IMC value (Kc = 0.6), and the derivative part was varied from 0.1 to 1000s to observe the effect of derivative part on Stiction. The variation of controllers parameters are shown in the Table 3.2.

Figure 3.4 shows the response of process. While applying a lower Kc after time 500s, the amplitude of the limit cycle decreased about 40%. But after that with the change of derivative part, there is no significant change in the frequency or amplitude of the limit cycle whether the derivative part is too high or low.

***Table 3.2** : Controller parameters for simulating the control loop as shown by Figure 3.3*

Time	Kc	Derivative part (D = Kc*τ_D)
0-500s	1	-
500-1000s	0.6	-
1000-1500s	0.6	2
1500-2000s	0.6	10
2000-2500s	0.6	50
2500-3000s	0.6	100
3000-3500s	0.6	500
3500-4000s	0.6	1000
4000-4500s	0.6	1
4500-5000s	0.6	0.1

From this observation it can be said that derivative controller has less effect on stiction. This is completely a disagreement with the stiff PD controller proposed by [13]. And it is also notable that using a proportional only controller with lower Kc has positive effect on Stiction. Now the question is what should be the value of Kc? In the successive sections of this chapter, the answer to this question was tried to find out.

3.2 Choosing the best Proportional only Controller Gain

From the previous section it can be said that Integral control action should be removed for handling valve stiction and derivative controller has no significant effect on stiction. It was also observed that Proportional Controller with lower Kc can handle the stiction better. But which should be the best value of Kc?

For this purpose, another SIMULINK model was designed by varying the Kc to check that which value of Kc gives the best result in handling Stiction. Figure 3.5 shows the block diagram of Model. The process was same as the before i.e. G(s) = $\frac{3e^{-5s}}{(5s+1)(10s+1)}$.

The IMC controller settings for this SOPTD process are as follows : $K_C = 0.6$, $\tau_I = 15s$, $\tau_D = 3.33s$.

Figure 3.5. A Closed Loop block diagram to compare the effects of different Kc on Stiction. For time, a) 0-500s Kc was 1, b) 500-1000s Kc was 2, c) 1000-1500s Kc was 5, d) 1500-2000s Kc was 10, e) 2000-2500s Kc was 0.8, f) 2500-3000s Kc was 0.6 (*Calculated by IMC method*), g) 3000-3500s Kc was 0.4, h) 3500-4000s Kc was 0.1, i) 4000-4500s Kc was 0.05 and j) 4500-5000s Kc was 0.01.Set point was changed after 50s from 4mA to 6mA.

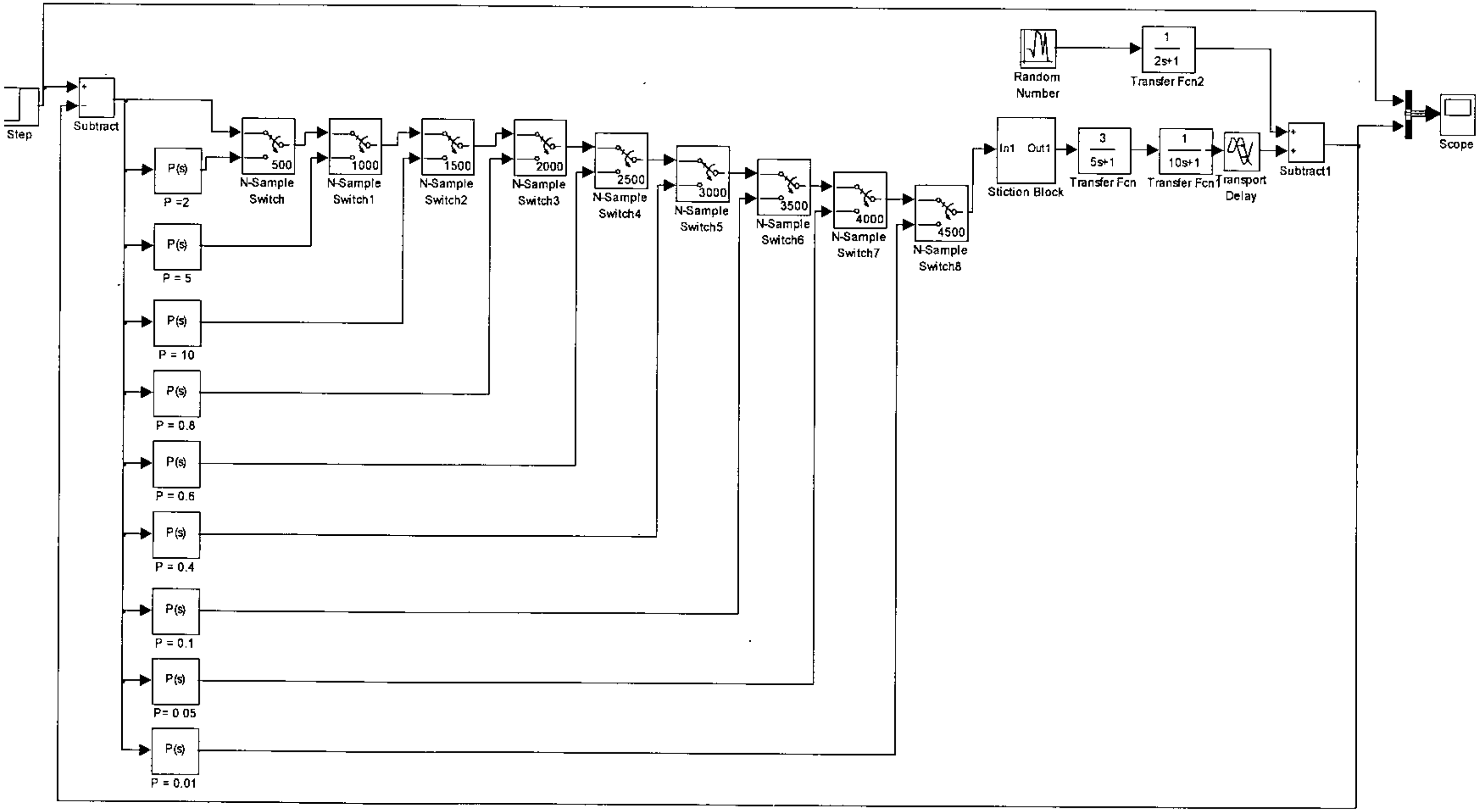


***Table 3.3** : Proportional only gains for simulating the control loop as shown by Figure 3.5*

Time	**Kc**
0-500s	1
500-1000s	2
1000-1500s	5
1500-2000s	10
2000-2500s	0.8
2500-3000s	0.6 (IMC)
3000-3500s	0.4
3500-4000s	0.1
4000-4500s	0.05
4500-5000s	0.01

Figure 3.6 shows the response of the process with the sticky valve on different Kc values. When Kc value was 1(time 0-500s), a decreasing but a limit cycle with average amplitude 4 was seen. Then Kc was increased to 2(time 500-1000s), a rapid increase in the limit cycle amplitude was observed (about 400% increase than when Kc = 1). As Kc was increased to 5 (time 1000-1500s) and then to 10 (time 1500-2000s), further increase in the limit cycle was observed.

Then Kc was decreased to 0.8 (time 2000-2500s). Sudden decrease in the initial limit cycle (Kc = 1) was observed by about 200%. When Kc was set to 0.6 as calculated by the IMC method (time 2500-3000s) further decrease in the limit cycle amplitude was seen. When Kc was also decreased slightly to 0.4, further decrease in the limit cycle amplitude and the frequency of the limit cycle was seen. It was previously said by [4] that the amplitude decrease with the cost of increase in the frequency. But this simulation result shows that if we can choose a proper Kc value both the amplitude and frequency can be decreased. By lowering the Kc value more, we find a complete absence of the limit cycle though there is an offset to the set point seen in the response.

Though an offset is present (pertaining an offset is the inherent criteria for a Proportional only Controller), but still the Proportional only controller can reduce or totally eliminate the limit cycle caused by a Sticky valve. So, this section concludes that Sticky valve can be handled in a better way till the next shut down of the process with the help of a Proportional only controller. In the subsequent section, it is tried to find out an empirical correlation for calculating Kc that will handle stiction with sufficient efficiency irrespective of the process parameters and degree of stiction.

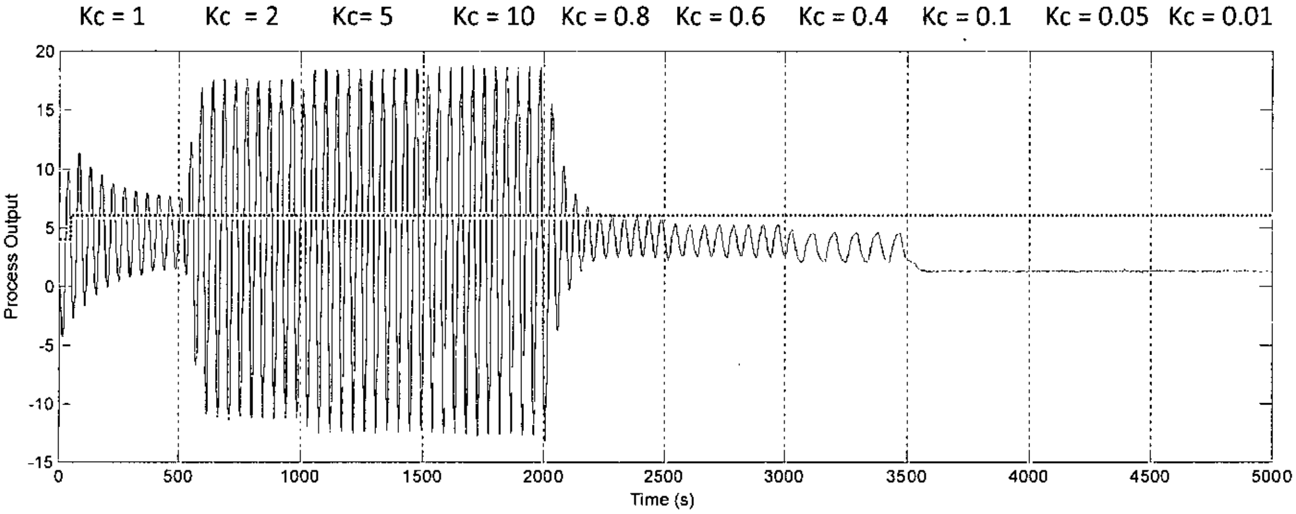


Figure 3.6. The response of the simulated closed loop block with 10 different Kc values on Stiction as shown in Figure 3.5. The dotted line indicates the desired process output(setpoint) and solid line indicates the simulated process output.

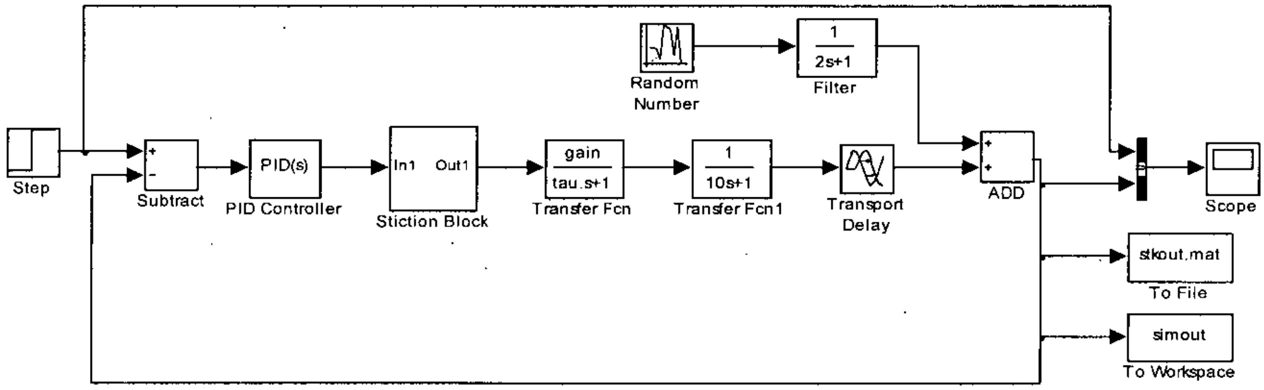


Figure 3.7. A General Closed Loop block diagram to get the average ratio between Kc and Process gain, Kc and Process time constant and Kc and Time delay. When the ratio of Kc and Process gain was to be obtained other two (tau = 5, delay = 5) were remained in their initial values and so on.

3.2.1 Derivation of the Empirical Correlation

There are hundreds or thousands of control loops in modern process plants. About 20-30% of the pneumatic valves suffer from stiction or other non-linearities. So, tuning each of the loops which are suffering from stiction will take a long time and also abrupt setup of controller parameters can cause serious upset to the process. Since this study focuses on efficient tuning of PID controllers, a starting guideline for this tuning was tried to develop in this section.

3.2.1.1 Formulation of Kc with Process parameters

To see the effect of changing Process Gain, Time Constant and Transport Delay on Kc; we have divided the SOPTD Transfer function into three parts as follows –

$$\frac{3}{5s+1} \times \frac{1}{10s+1} \times e^{-5s} \text{.........}\textbf{(3.3)}$$

To reduce the computational effort $\frac{1}{10s+1}$ was kept fixed. The gain and time constant of the first part and time delay of the third part were varied. So, the SOPTD becomes

$$\frac{gain}{tau.s+1} \times \frac{1}{10s+1} \times e^{-delay.s} \text{..}\textbf{(3.4)}$$

Table 3.4 : *Variation of Kc and Process gain (Kp) for determining the best ratio of Kc/Kp.*

Process Gain, Kp	Time Constant, τ	Time Delay, θ	Controller gain, Kc
0.5	0.5	0.5	0.05
1.0	1.0	1.0	0.10
1.5	1.5	1.5	0.15
2.0	2.0	2.0	0.20
2.5	2.5	2.5	0.25
3.0	3.0	3.0	0.30
3.5	3.5	3.5	0.35
4.0	4.0	4.0	0.40
4.5	4.5	4.5	0.45
5.0	5.0	5.0	0.50
5.5	5.5	5.5	0.55
6.0	6.0	6.0	0.60
6.5	6.5	6.5	0.65
7.0	7.0	7.0	0.70
7.5	7.5	7.5	0.75
8.0	8.0	8.0	0.80
8.5	8.5	8.5	0.85
9.0	9.0	9.0	0.90
9.5	9.5	9.5	0.95
10	10	10	1.0
20	20	-	2
30	30	-	3
40	40	-	4
50	50	-	5
100	100	-	10
-	-	-	20

Effect of changing process gain on controller gain was investigated by simulating the SIMULINK model of Figure 3.7 with variable Kc and variable gain whereas keeping the Time Constant and Transport delay fixed to their original values, i.e, tau = 5, delay = 5 and hence the following process was simulated against the variable Kc :

$$\frac{gain}{5s+1} \times \frac{1}{10s+1} \times e^{-5s} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.5)$$

Here, Kc was varied from 0.05 to 1 with an increment of 0.05 and then to 2,3,4,5, 10 and 20. Process gain was varied from 0.5 to 10 with an increment of 0.5 and then to 20, 30, 40, 50 and 100. Table 3.4 shows the variation of controller gain with the process gain. So, 25 different process gains were tried against 26 controller gains and amplitude of each of these 650 (=25 x 26) combinations were examined. Among those whose amplitudes were between the ± 30% of the desired set point, i.e in between 0.7 to 1.3 (since here the setpoint was 1) ratios (Kc/Kp for each combination) of those combinations were averaged to get the best ratio between the controller gain and the process gain and it was found as 1.56. The data table for this averaging process is shown in Table A.1 of Appendix A.

In a similar manner, the ratio between Kc and process time constant was obtained by simulating the following process

$$\frac{3}{tau.s+1} \times \frac{1}{10s+1} \times e^{-5s} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.6)$$

In this case Kc was varied from 0.05 to 1 with an increment of 0.05 and then to 2,3,4,5, 10 and 20. Process time constant (τ) was varied from 0.5 to 10 with an increment of 0.5 and then to 20, 30, 40, 50 and 100. Table 3.5 shows the variation of Kc and τ in a brief manner. The average ratio of Kc to τ was found as 0.033 by processing 650 combinations of Kc and τ as in the case of Kc and Kp. The data table for this averaging process is shown in Table A.4 of Appendix A.

For the ratio between Kc and time delay (θ),

$$\frac{3}{5s+1} \times \frac{1}{10s+1} \times e^{-delay.s} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.7)$$

equation 3.7 was simulated against variable Kc (0.05 to 1 with an increment of 0.05 and then to 2,3,4,5, 10 and 20). Here, time delay was varied from 0.5 to 10 with an increment of 0.5. Table 3.6 shows this variation. In this case the average ratio of Kc to delay was found as 0.053 after processing 520 (= 26 x 20) combinations of Kc and θ within the tolerance limit (± 30%). The data table for this averaging process is annexed as Table A.5 of Appendix A.

Table 3.5 *: Variation of Kc and Process Time Constant (τ) for determining the best ratio of Kc/Kp.*

Time Constant, τ	**Kc**
0.5	0.05
1.0	0.10
1.5	0.15
2.0	0.20
2.5	0.25
3.0	0.30
3.5	0.35
4.0	0.40
4.5	0.45
5.0	0.50
5.5	0.55
6.0	0.60
6.5	0.65
7.0	0.70
7.5	0.75
8.0	0.80
8.5	0.85
9.0	0.90
9.5	0.95
10	1.0
20	2
30	3
40	4
50	5
100	10
-	20

Therefore, three relations are obtained from which Kc can be calculated.

Kc = 0.053*Delay...................(A)

Kc = 1.56*Gain.......................(B)

Kc = 0.033*Time Constant........ (C)

Now the question is which value of Kc should we use? We prefer the minimum of these three Kc values, since it was previously found that the smallest value of Kc gives the best result. So, our proposed method is as follows –

Kc = minimum(0.053*Delay, 1.56*Gain, 0.033*Time Constant)......(3.8)

Table 3.6 *: Variation of Kc and Process Time Delay (θ) for determining the best ratio of Kc/Kp.*

Time Delay, θ	**Kc**
0.5	0.05
1.0	0.10
1.5	0.15
2.0	0.20
2.5	0.25
3.0	0.30
3.5	0.35
4.0	0.40
4.5	0.45
5.0	0.50
5.5	0.55
6.0	0.60
6.5	0.65
7.0	0.70
7.5	0.75
8.0	0.80
8.5	0.85
9.0	0.90
9.5	0.95
10	1.0
-	2
-	3
-	4
-	5
-	10
-	20

3.2.1.2 Evaluation of the Proposed Method

The proposed method was simulated against variable Process Gain, Process Time Constant and Time Delay. Kc calculated from our model was also compared with the Kc calculated from the IMC value. We have also compared our model results with some low end fixed values of Kc like 0.1, 0.15, 0.2 and 0.25.

Figure 3.8 demonstrates the SIMULINK model block used for this validation purpose. In this case process gain was varied from 1 to 10 with an increment of 1 and then to 20 & 50, process time constant was varied similarly as the process gain and process time delay was varied from 0.5 to 10 with an increment of 0.5. The variation of process parameters are given in Table 3.8.

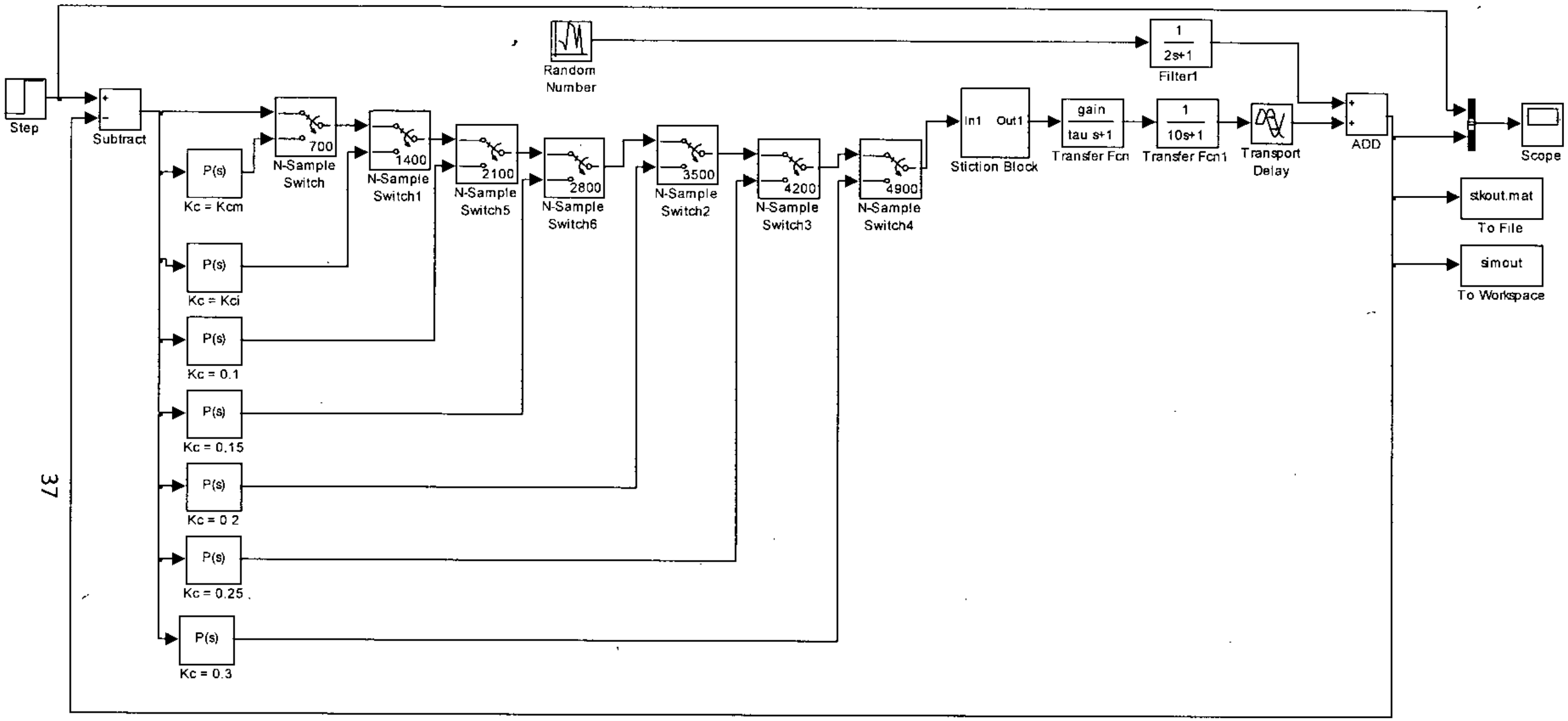


Figure 3.8. A Closed Loop block diagram to check the effects of Kc calculated from the proposed model on Stiction. For time, a) 0-700s Kc was 1, b) 700-1400s Kc was as Calculated from the proposed model (equation 3.8), c) 1400-2100s Kc was as Calculated from IMC method, d) 2100-2800s Kc was 0.1, e) 2800-3500s Kc was 0.15, f) 3500-4200s Kc was 0.20, g) 4200-4900s Kc was 0.25, h) 4900-5600s Kc was 0.3. Here, setpoint was changed from 0% to 1% after the first 300s. To avoid the interference problem, placement of the PID controllers were shuffled during some simulations as in Figure 3.10, 3.12, 3.14, 3.15 and 3.16.

***Table 3.7** : Proportional only gains for simulating the control loop as shown by Figure 3.8*

Time	Kc
0-700s	1
700-1400s	Kcm (as calculated by equation 3.5)
1400-2100s	Kci (as calculated by IMC method)
2100-2800s	0.10
2800-3500s	0.15
3500-4200s	0.20
4200-4900s	0.25
4900-5600s	0.30

From Table 3.8 it is clear that the proposed model was checked with (12 x 12 x 20 = 2880 different SOPTD process models. Among these 2880 results only the limiting cases of are shown from Figure 3.9 to Figure 3.17 to check the validity of this model. Here, it should be noted that the proposed model was compared with Kc value as calculated by the IMC method and also some other low Kc values.

***Table 3.8** : Variation of Process parameters for simulating as in Figure 3.8.*

Time Delay, θ	Time Constant, τ	Process Gain, Kp
0.5	1	1
1.0	2	2
1.5	3	3
2.0	4	4
2.5	5	5
3.0	6	6
3.5	7	7
4.0	8	8
4.5	9	9
5.0	10	10
5.5	20	20
6.0	50	50
6.5	-	-
7.0	-	-
7.5	-	-
8.0	-	-
8.5	-	-
9.0	-	-
9.5	-	-
10	-	-

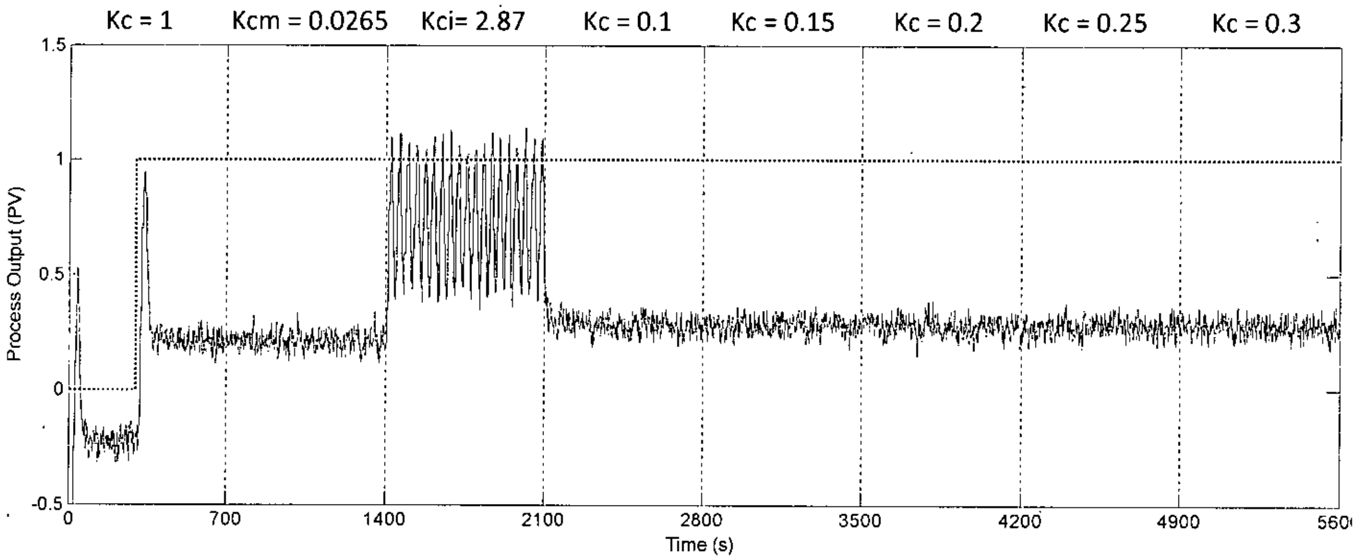


Figure 3.9. Effect of different proportional controller, when process gain = 1, tau = 1 and delay = 0.5 of equation 3.4. After 300s, the set point was changed from 0 to 1. Here, it is seen that all the values of Proportional Controller (including the value from the Proposed model and Kc =1) are useful to eliminate the effect of sticiton with the cost of some offset except the Proportional Controller as calculated from the IMC model (Kci), which introduces oscillation since in this case the IMC value of Kc is too high (2.87).

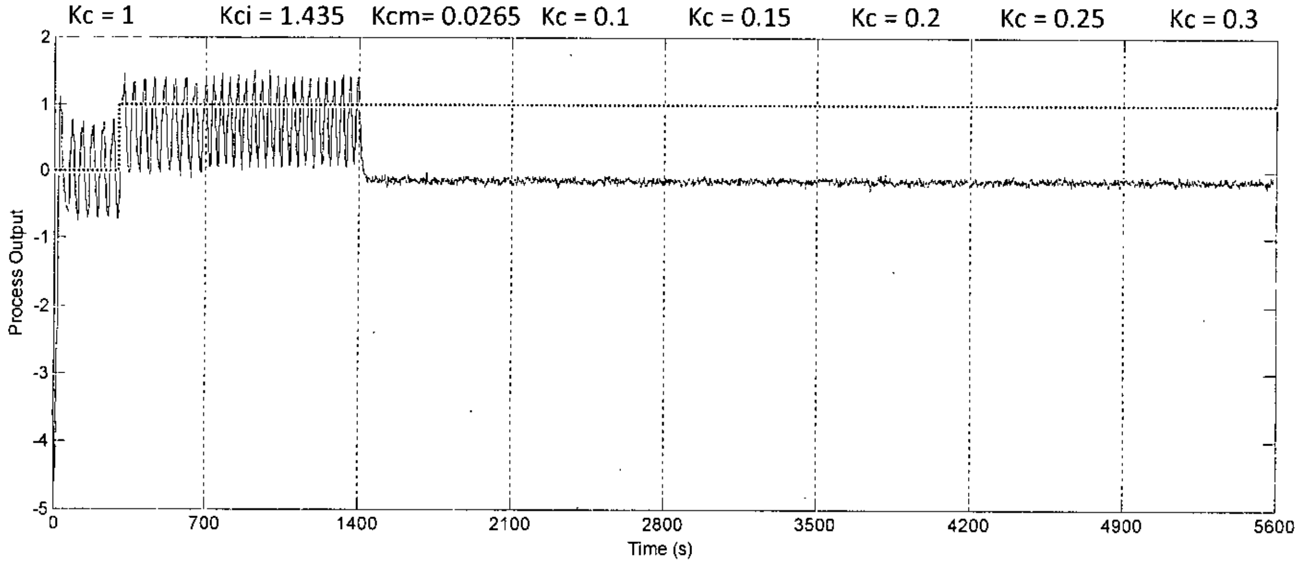


Figure 3.10. Effect of different proportional controller when process gain = 2, tau = 1 and delay = 0.5 of equation 3.4. After 300s, the set point was changed from 0 to 1. Here, it is seen that Kc value lower than or equals to 0.3 worked well to eliminate stiction though it has introduced some offset. Here, the offset is in the negative side.

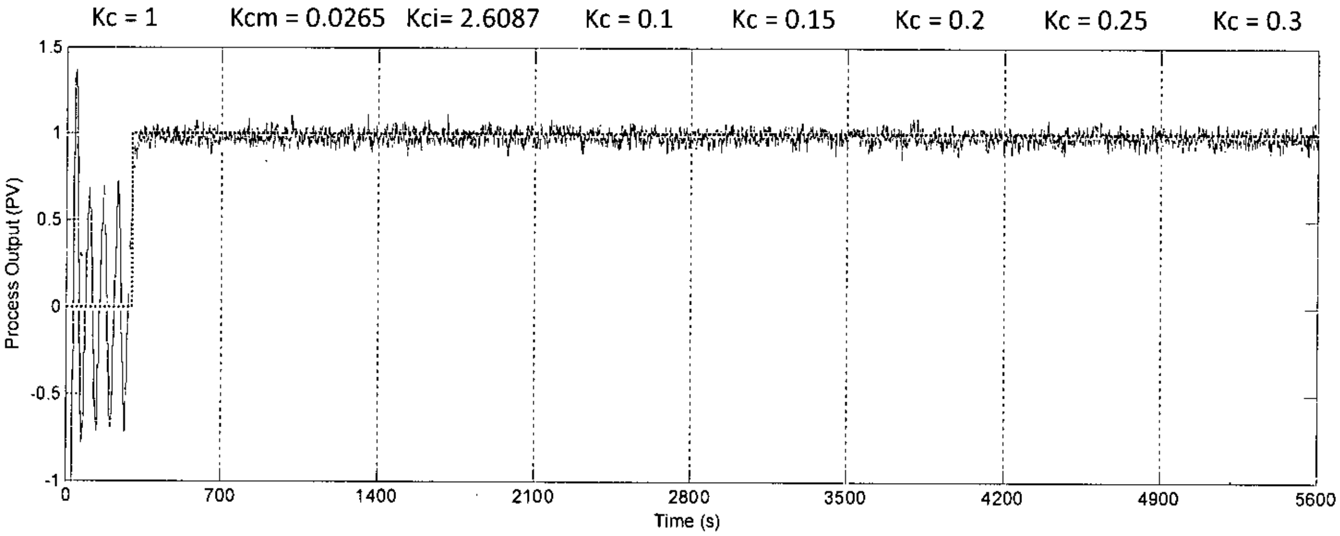


Figure 3.11. Effect of different proportional controller when process gain = 2, tau = 10 and delay = 0.5 of equation 3.4. After 300s, the set point was changed from 0 to 1. And for all the values of Proportional Controller (including the value from the Proposed model) are useful to eliminate the effect of sticiton with efficient setpoint tracking.

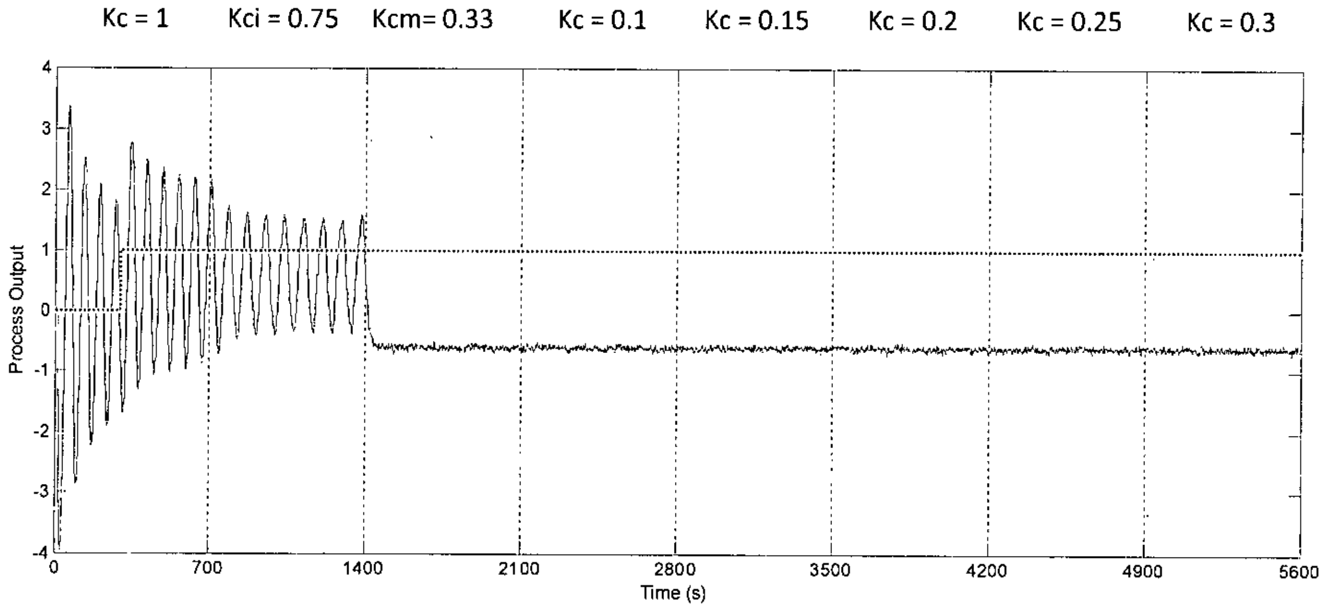


Figure 3.12. Effect of different proportional controller when process gain = 2, tau = 10 and delay = 10 of equation 3.4. After 300s, the set point was changed from 0 to 1. Here, it is seen that after Kc in the range of 0.3 works well to eliminate the oscillation though some offset is introduced. Here, the offset is in the negative side and it is slightly larger than that of Figure 3.10.

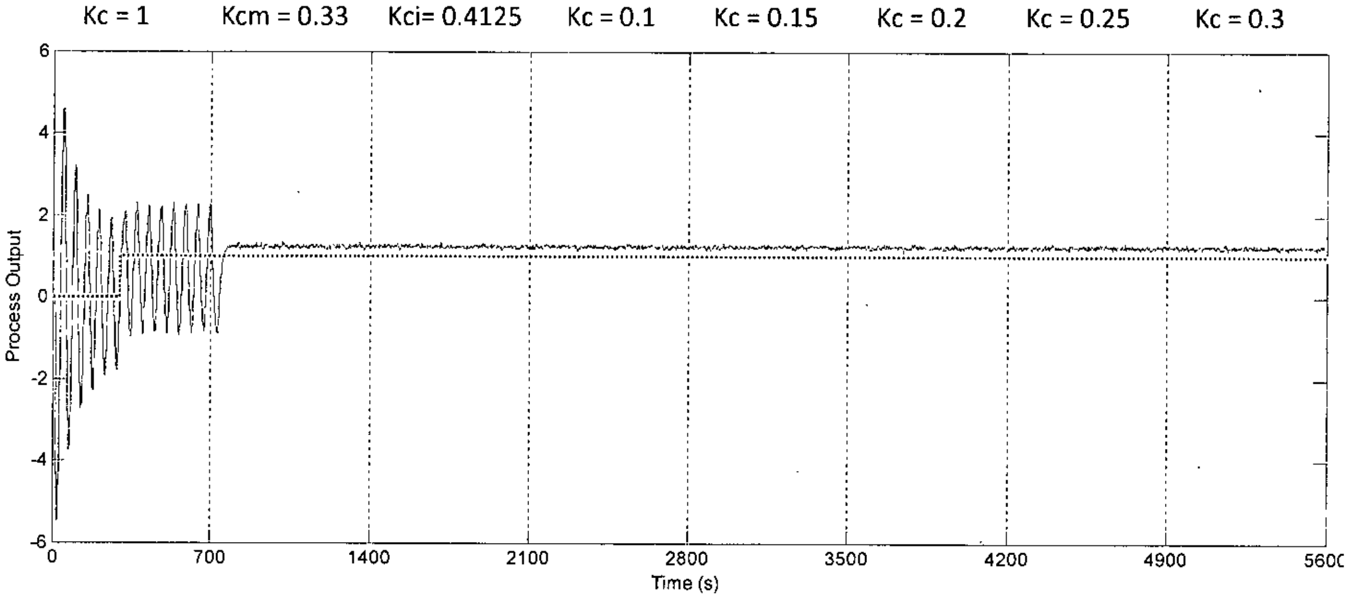


Figure 3.13. Effect of different proportional controller when process gain = 2, tau = 1 and delay = 10 of equation 3.4. After 300s, the set point was changed from 0 to 1. Here, it is seen that after the first 700s (when Kc = 1), all other low value Proportional Controller (including the value from the Proposed model) are useful to eliminate the effect of Sticiton with the cost of some offset. In this case the offset is in positive side.

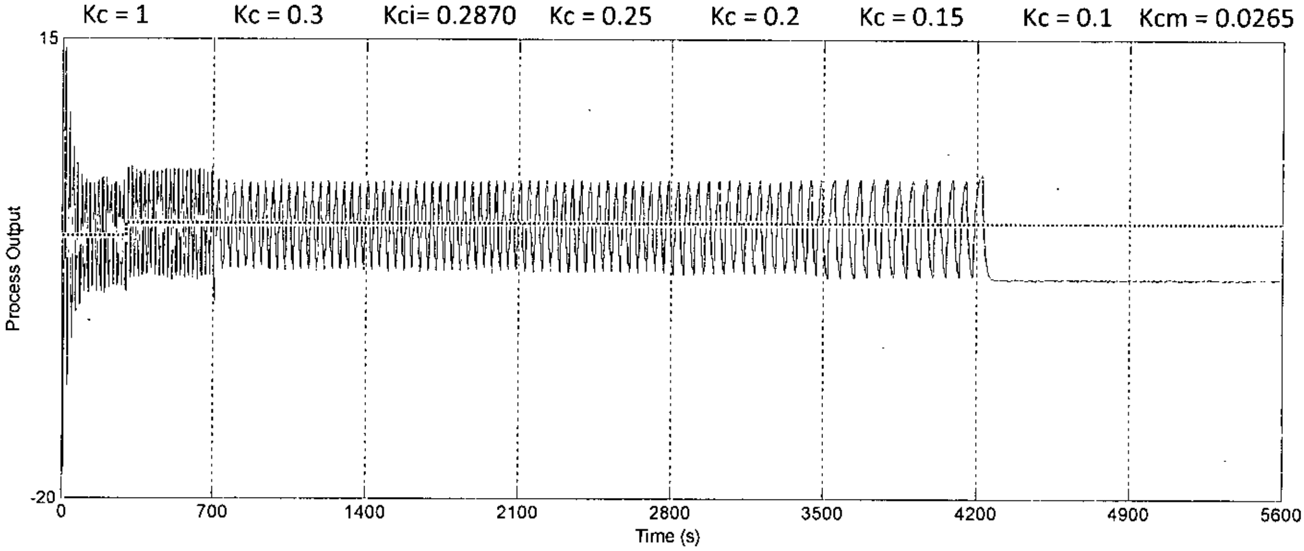


Figure 3.14. Effect of different proportional controller when process gain = 10, tau = 1 and delay = 0.5 of equation 3.4. Here, oscillation was eliminated when Kc was 0.1 or lesser. From time 4200s Kc was 0.1 and from time 4900s when Kcm (Kc calculated from the proposed correlation) was 0.0265, the simulated process showed the best result.

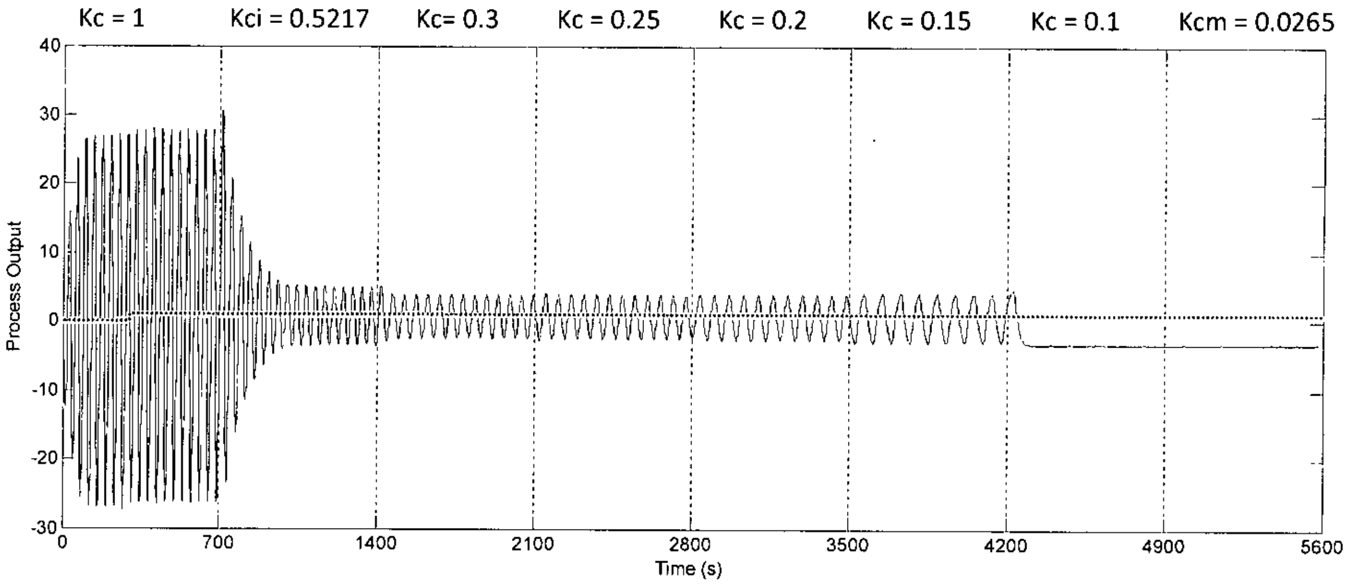


Figure 3.15. Effect of different proportional controller, when process gain = 10, tau = 10 and delay = 0.5 of equation 3.4. After 300s, the set point was changed from 0 to 1. Here, is seen that Kc value equals to or lower than 0.1 worked well to eliminate the oscillation. Kc value in the order of 0.5 also reduces the oscillation about 5 times. Kcm (Kc value calculated from the proposed correlation) also worked well in this case.

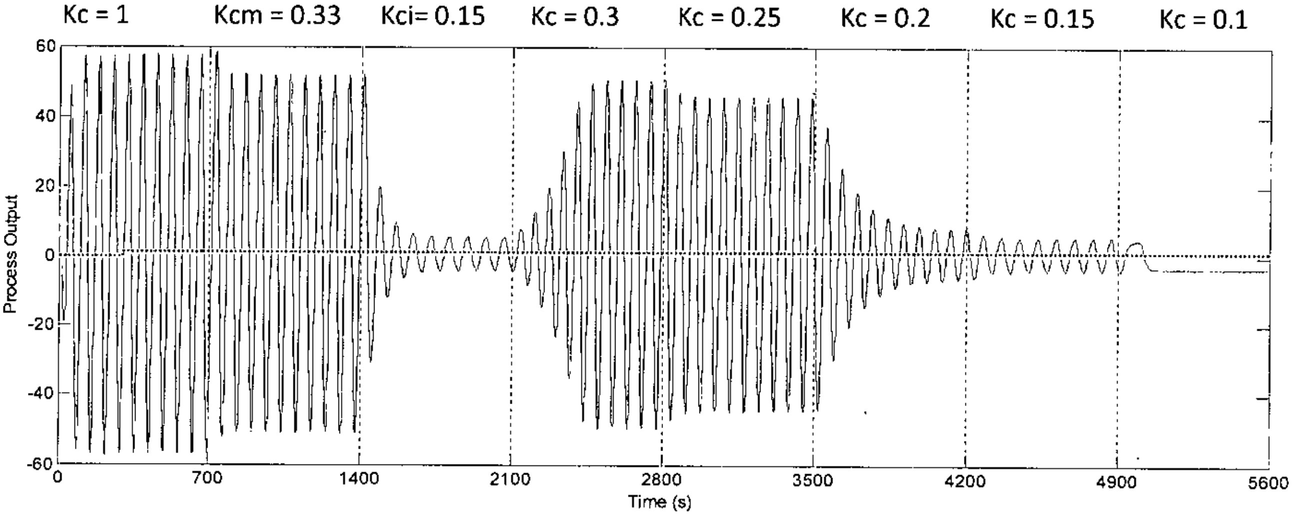


Figure 3.16. Effect of different proportional controller, when process gain = 10, tau = 10 and delay = 10 of equation 3.4. After 300s, the set point was changed from 0 to 1. Here, it is seen that Kc lower than 0.2 reduces the oscillation and Kc = 0.1 eliminates the oscillation.

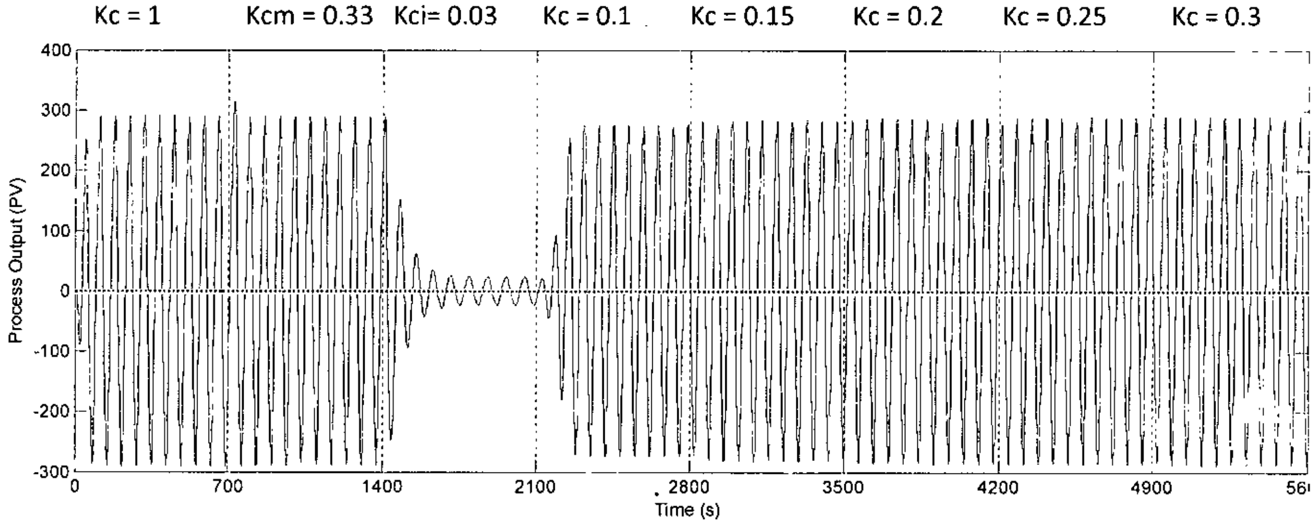


Figure 3.17. Effect of different proportional controller, when process gain = 50, tau = 10 and delay = 10 of equation 3.4. After 300s, the set point was changed from 0 to 1. Here, it is seen that all the Kc values give high magnitude of Oscillation, whereas the Oscillation produced by the Proportional gain that was calculated by the IMC method (Kci = 0.03) is quite low (comparing with others). In this case the, the Kc value from IMC method was found to be very low as 0.03.

From Figure 3.9 it is observed that all proportional controllers except the controller designed by the IMC method (Kci) are useful to eliminate the effect of stiction with the cost of some offset. Here the IMC controller introduces oscillation since in this case the IMC value of Kc is too high (2.87). One important thing to note that with low process gain, higher value of Kc reduces the oscillation even with less offset (see first 300s of Figure 3.9). It is seen from Figure 3.10 that Kc value lower than or equals to 0.3 worked well to eliminate stiction though it has introduced some offset. Here, the offset is in the negative side. Here, Kcm is the Kc value calculated by the proposed correlation.

From Figure 3.11 it is seen that, all the values of Proportional Controller (including the value from the proposed model) are useful to eliminate the effect of Stiction. Here, it is seen that when Kc was initially 1, there was some oscillation, but after the set point change, the oscillation was totally nullified. In this case, set point was tracked perfectly also. The reason behind this phenomenon is probably the process parameters. Here, time constant was much higher than gain and delay. From the proposed correlation it is observed that time constant has the lowest effect on Kc value. From Figure 3.12, it is seen that after Kc in the range of 0.3 works well to eliminate the oscillation though some offset is introduced. Here, the offset is in the negative side and it is slightly larger than that of Figure 3.10.

From Figure 3.13 it is seen that after the first 700s (when Kc = 1), other low values of proportional controllers (including the value from the Proposed model/correlation, Kcm) are useful to eliminate the effect of stiction with the cost of some offset. In this case the offset is in positive side and the amount of offset is smaller than that showed by Figure 3.10.

From Figure 3.14 it is seen that oscillation was eliminated when Kc was 0.1 or lesser. From time 4200s Kc was 0.1 and from time 4900s when Kcm (Kc calculated from the proposed correlation) was 0.0265, the simulated process showed the best result. Figure 3.15 shows the similar trend. In this case it is seen that Kc value equals to or lower than 0.1 worked well to eliminate the oscillation. Kc value in the order of 0.5 also reduces the oscillation about 5 times. Kcm also worked well in this case.

From Figure 3.16 it is seen that Here, it is seen that Kc lower than 0.2 reduces the oscillation and Kc = 0.1 eliminates the oscillation. From Figure 3.17, it is seen that all the Kc values give high magnitude of oscillation, whereas the oscillation produced by the Proportional gain that was calculated by the IMC method (Kci = 0.03) is quite low (comparing with others). In this case, the Kc value from IMC method was found to be very low as 0.03.

These figures reveals that no proportional gain itself is sufficient to handle the stiction for the all the ranges of Process parameters. The proposed model can handle oscillation upto a process gain value of 10 when the time delay is very low (see Figure 3.9 to 3.15). When time delay increases along with the Process gain, the proposed model also produces oscillatory responses (See Figure 3.16 and 3.17). In case of Figure 3.9 the process gain was low i.e., and in that case using a low Kc does not bring good results.

The Kc value calculated from the IMC model produces some oscillations even with very low process parameters (Figure 3.9). In fact, in case of low process parameters all the Proportional gains showed good result except the IMC model(Kci = 2.87). But when the process gain was as high as 50, the IMC model showed the best result because in that case the value of the proportional gain from the IMC model was calculated as low as 0.03 which is more than three times lower than the fixed value proportional gain of 0.1. In this case the proportional gain calculated from the proposed model was found as 0.33.

The fixed low value proportional gains specially 0.1, showed good results till the very high process gain having a value of 50. Also, the Kc value from the proposed correlation showed good results until a high process gain and time delay combines together. When process gain was 50, even the proportional gain of 0.03 (by IMC method) showed a good amount of oscillation. Again it is interesting to note that with low process gain, low value of Kc gives larger offset. In fact when process gain Kp is 1, Kc = 1 gives the best result (for the first 300s

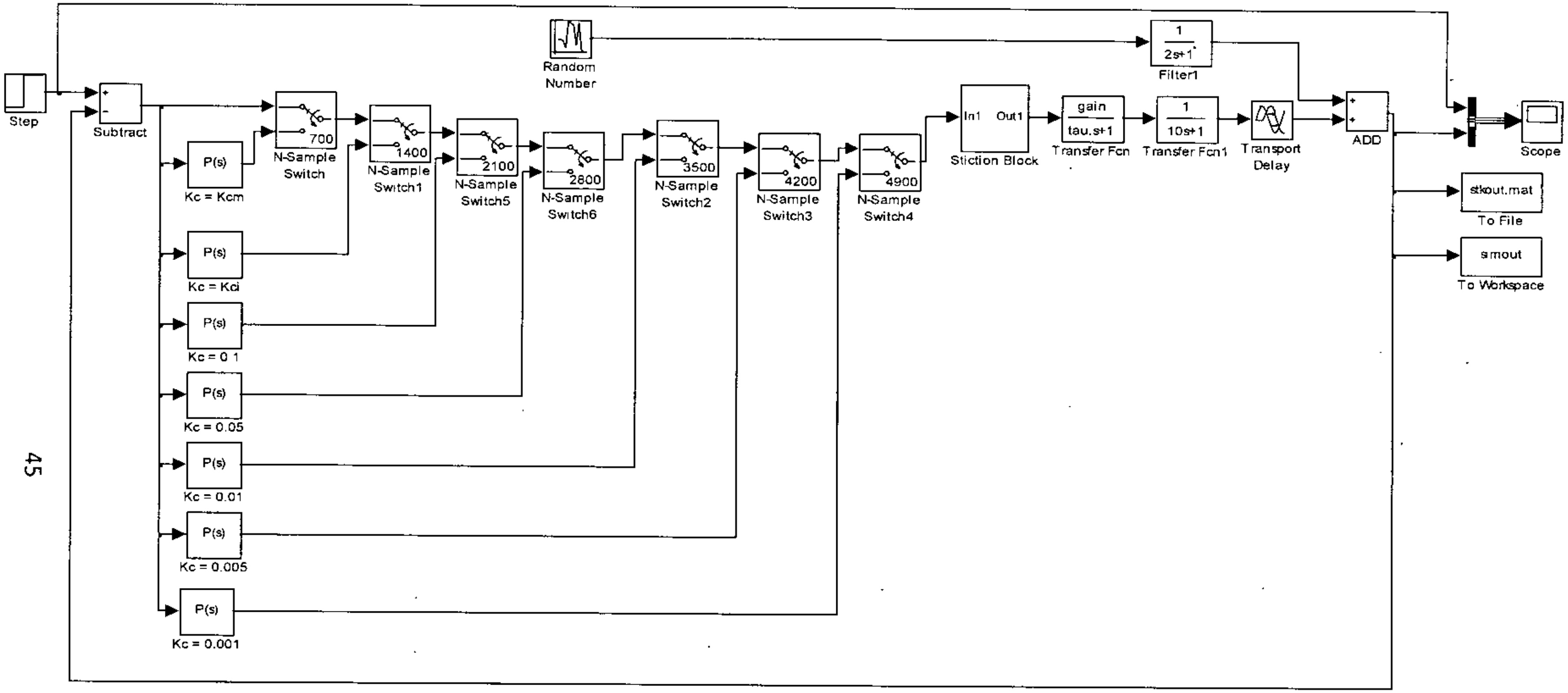


Figure 3.18. A Closed Loop block diagram to check the effects of Kc calculated from the proposed model on Stiction. For time, a) 0-700s Kc was 1, b) 700-1400s Kc was as Calculated from the proposed model (equation 3), c) 1400-2100s Kc was as Calculated from IMC method, d) 2100-2800s Kc was 0.1, e) 2800-3500s Kc was 0.05, f) 3500-4200s Kc was 0.01, g) 4200-4900s Kc was 0.005, h) 4900-5600s Kc was 0.001. Here, setpoint was changed from 4mA to 6mA after the first 300s.

till the set point was changed) as it is depicted by Figure 3.9. But for higher process gain, values lower than 0.03 of Kc is required to completely nullify the oscillation. Another interesting observation is that process gain has greater effect on Kc other than time constant or time delay. Time constant has the lowest effect on Kc.

3.3 Refining the Proposed method based on the simulation result

From the previous sections one important result is found that a Proportional only Controller with a lower value can handle the sticky valve very effectively with the price of some offset. But the suitability of a lower value for a given process might vary depending on the process condition, percentage of stiction and so on. In a large process industries there might be hundreds of valves. So, tuning the Kc value for each valve will not only be time consuming but also a very difficult task.

3.3.1 Improving the Proportional Only Controller

In the previous section it is seen that the proposed method for compensating compensation worked within a limit of process parameters, specially the process gain. From Figure 3.17, it is also found that a very low value (0.03) of proportional gain can handle a process with high process gain, Time constant and delay. That triggered the idea of designing a Proportional Controller with a very low but fixed proportional gain. For this purpose a modified version of simulation model shown in (Figure 3.18) was used here to check the effect of very low proportional controller for the same process for which Figure 3.19 was generated i.e. ($\frac{50}{10s+1}\times\frac{1}{10s+1}\times e^{-10s}$).

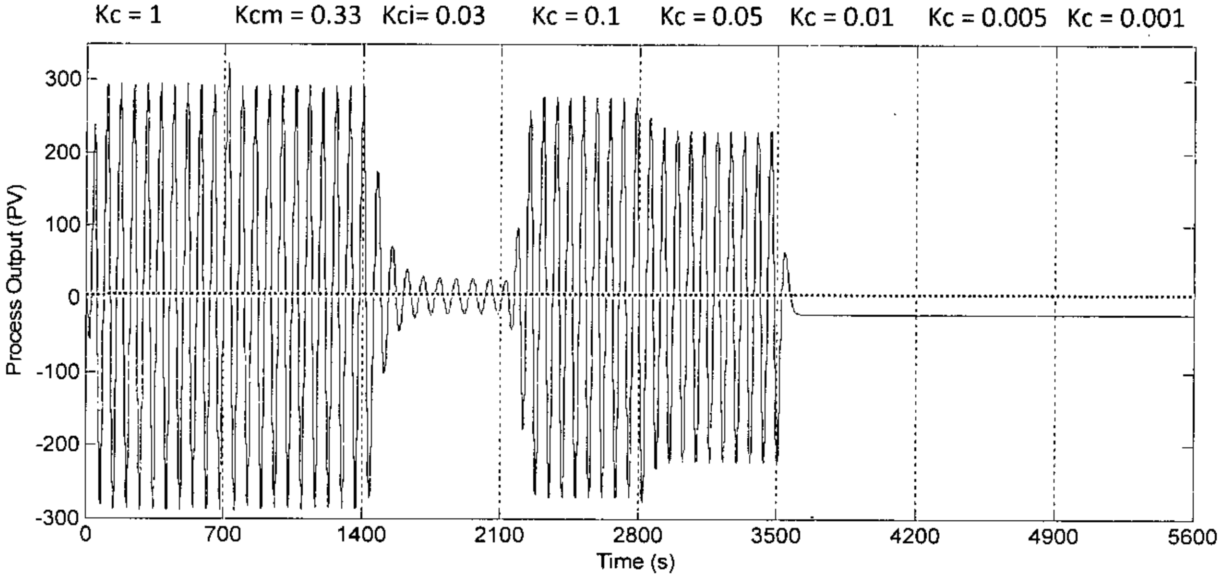


Figure 3.19. Response of the process for the Simulation Block of Figure 3.18.

Figure 3.19 shows the simulation result of the process block diagram as in Figure 3.18. It shows that amplitude of oscillation due to stiction is very high (in the range of 300) for controller gain (K_c) = 1 (time 1s-700s), for controller gain as calculated from the proposed model (Kcm = 0.33, time = 701s-1400s), for K_c = 0.1 (time 2101s-2800s), for K_c = 0.05 (time 2801s-3500s). However, the amplitude was quite low for the controller gain as calculated from the IMC method (Kci = 0.03, time 1401s-2100s). The oscillation was quite absent for lower values of Kc, i.e. Kc = 0.01 (time 3501s-4200s), Kc = 0.005 (time 4201s-4900s) and Kc = 0.001 (time 4901s-5600s). But of course, this no-oscillation response occurred with the cost of some offset.

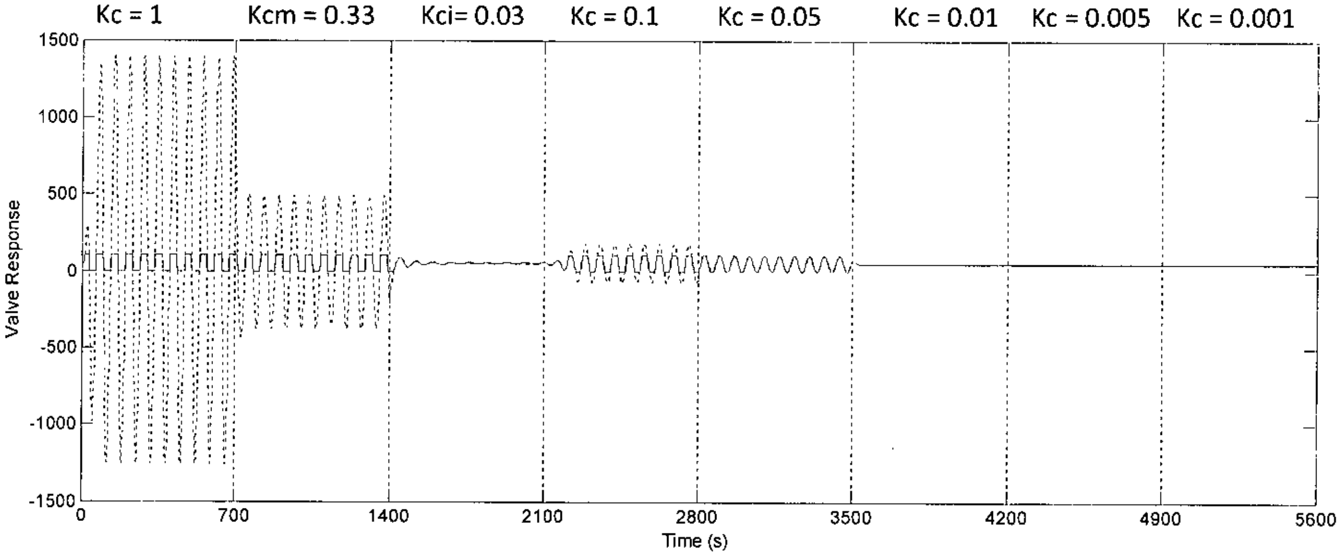


Figure 3.20. Simulated Response of the valve stem for the Simulation Block of Figure 3.18 Here, dotted line is the controller output. Solid black line is the simulated valve response.

Figure 3.20 shows the simulated response of the valve stem while checking the effects of using very low proportional only controllers. It shows that the stem remains stationary when the process shows no oscillation i.e. $K_c \leq 0.01$.

The effect of very low proportional gain on different process parameters of a SOPTD system has been examined further. For this purpose a very simple SIMULINK model was designed as in Figure 3.21. In this simulation, two very low proportional gains were passed through nine different sets of SOPTD processes in closed loop. Time duration for each set of SOPTD parameters was 500s. For the first 4500 seconds there was no controller in action (Proportional gain,K_c = 1). After 4500 seconds, a proportional controller with Controller Gain 0.01 was activated. After 9000 seconds, the Proportional Gain was lowered again to 0.001. All these three configurations of controller sent signal through the following nine sets of SOPTD processes ($\frac{gain}{tau.s+1} \times \frac{1}{10s+1} \times e^{-delay.s}$)., shown in Table 3.9.

Table 3.9. Parameter settings for different SOPTD processes to check the effect of low proportional only controller with different SOPTD processes in presence of stiction.

Gain	Tau	Delay	Simulation Time		
			No Controller (Kc = 1)	Kc = 0.01	Kc = 0.001
2	1	0.5	1-500s	4501-5000s	9001-9500s
2	10	0.5	501-1000s	5001-5500s	9501-10000s
2	10	10	1001-1500s	5501-6000s	10001-10500s
5	1	0.5	1501-2000s	6001-6500s	10501-11000s
5	10	0.5	2001-2500s,	6501-7000s	11001-11500s
5	10	10	2501-3000s	7001-7500s	11501-12000s
10	1	0.5	3001-3500s	7501-8000s	12001-12500s
10	10	0.5	3501-4000s	8001-8500s	12501-13000s
10	10	10	4001-4500s	8501-9000s	13001-13500s

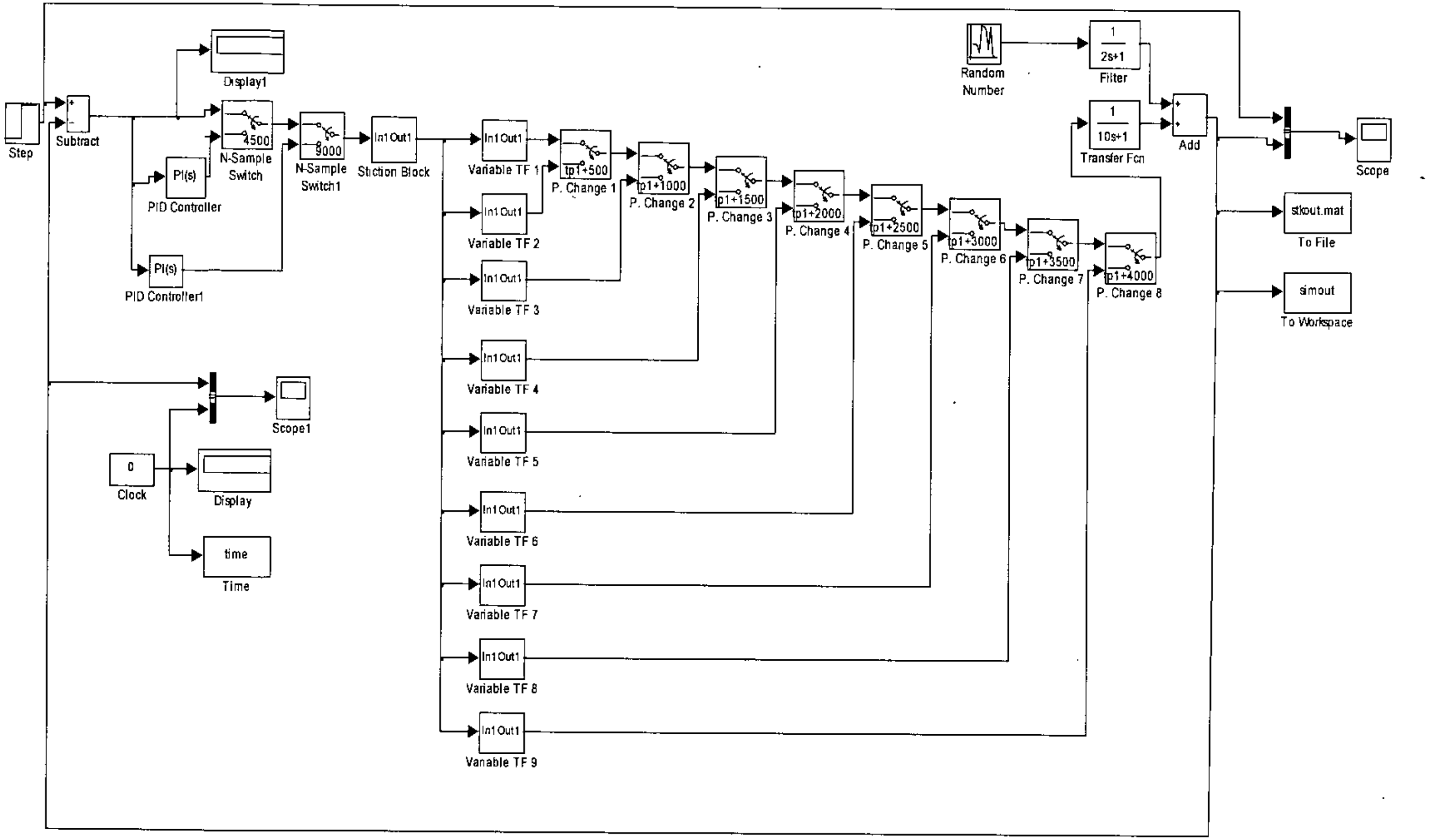


Figure 3.21. Simulink Block Diagram for Simulating Stiction with very Low Proportional only Controller.

Here, for the first 500s, 4501-5000s and 9001-9500s the process was $\frac{2}{s+1} \times \frac{1}{10s+1} \times e^{-0.5s}$. Similarly, for 501-1000s, 5001-5500s and 9501-10000s the process was $\frac{2}{10s+1} \times \frac{1}{10s+1} \times e^{-0.5s}$ and so on. The setpoint was changed from 4 mA – 8 mA after 300s.

The response of this simulation is shown in Figure 3.22. From this figure it is seen that for the first 1500s (K_c=1, Process gain = 2) the amplitude of limit cycle caused by Stiction is in the range of 1 from the mean, whereas there is very little increase in amplitude with the increase of process time constant (tau) 10 times. But there is significant amount of increase in the amplitude of oscillation with 20 times increase in Process time delay.

Then for 1501-3000s (Kc = 1 and Process gain = 5), the amplitude of the limit cycle is almost doubled whereas the process gain has increased for 2.5 times. In this case also, the effect of increase of Process time constant is not so significant but the effect of increase of time delay is much more significant. In this case, the amplitude has increased about 10 times.

Then for 3001-4500s (Kc = 1 and Process gain = 10), the amplitude of the limit cycle is doubled again whereas the process gain has increased for 2 times. In this case, the effect of increase of Process Time Constant is significant (about 5.5 times) but the effect of increase of Time Delay is much more significant. In this case, the amplitude has increased about 11 times.

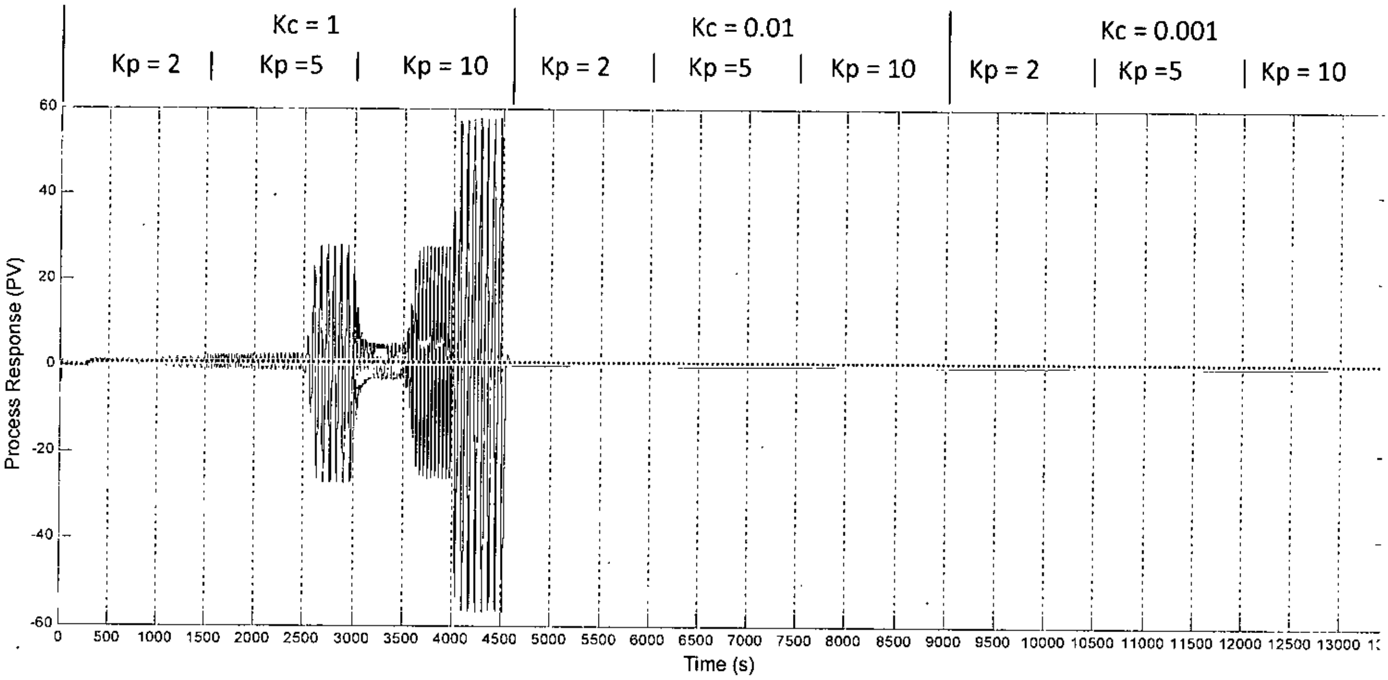


Figure 3.22. Response of the process for the Simulation Block of Figure 3.21. Here, dotted line is the desired process output (setpoint). Solid black line is the simulated process output.

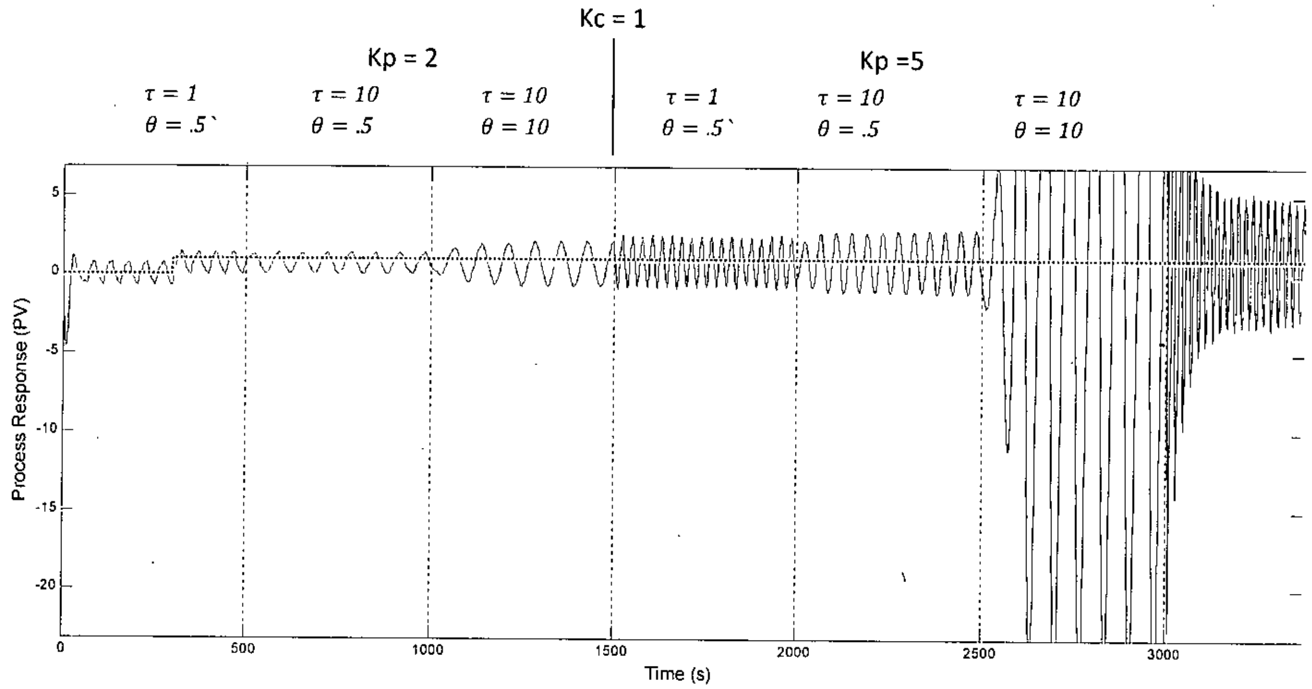


Figure 3.22a. Enlarged view of the initial 3000 seconds of Figure 3.22.

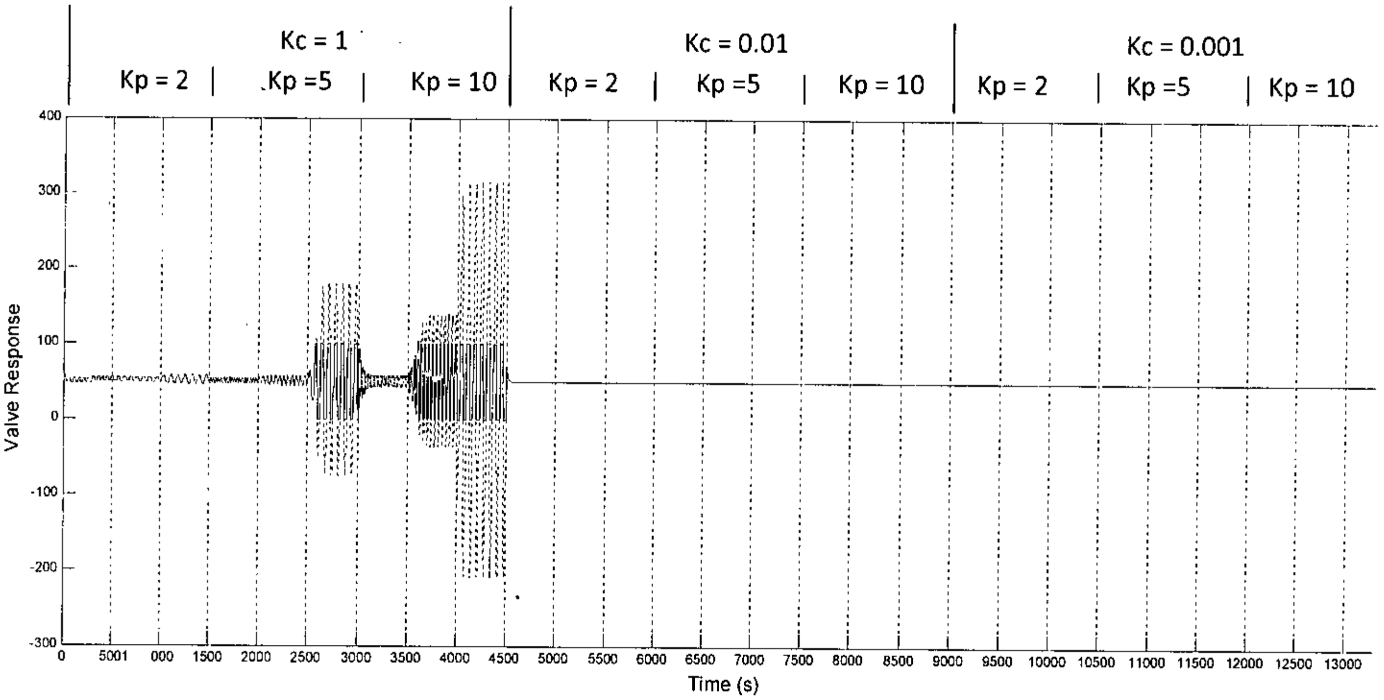


Figure 3.23. Simulated Response of the valve stem for the Simulation Block of Figure 3.21. Here, dotted line is the controller output. Solid black line is the simulated valve response.

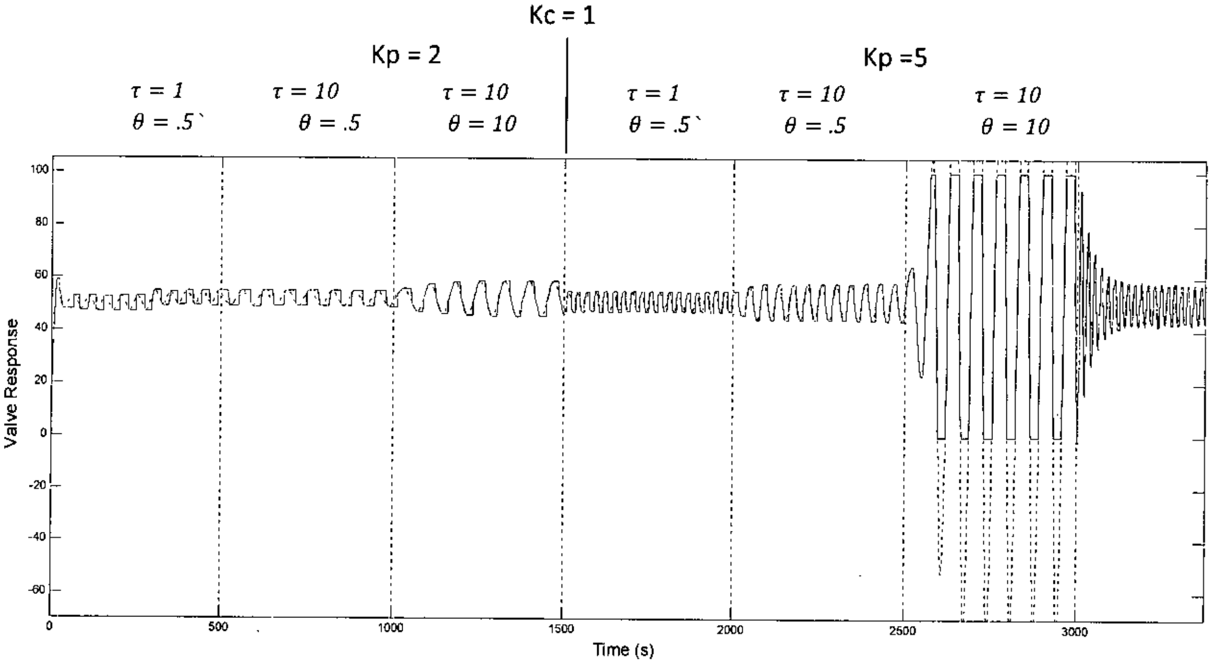


Figure 3.23a. Enlarged view of the initial 3000 seconds of Figure 3.23.

After 4500s, when Kc = 0.01 the oscillation becomes nil though some offset exists there, and after 9000s, when Kc = 0.001, the oscillation is still nil with some offset. So from this result, it can be concluded that using a proportional gain of value 0.01 will give a satisfactory result in handling stiction. Though there is still the existence of offset and experimental validation is required for this claim.

3.3.2 Reducing offset caused by the Proportional only Controller

Since, offset from the setpoint is an inherent feature of proportional only controller, proportional only controller is not suitable for industrial purpose. Because in that case maintaining the quality of product will be difficult. But handling a fixed offset rather than an oscillating offset is easier. In that sense, these results are worthy of some credit.

To reduce offset normally integral part is added with the proportional part. But chapter three shows that integral part should be avoided in case of stiction. So, it was tried to find out an optimized value of Integral part of a PID controller so that it will track the set point without deteriorating the limit cycle condition.

To check the effect of introducing very high integral time, i.e. very low integral effect, the same simulink model was used as shown in Figure 3.21.

***Table* 3.10**. Parameter settings for different SOPTD processes to examine the effect of low integral action on different SOPTD processes in presence of Stiction.

Gain	**Tau**	**Delay**	**Simulation Time**		
			No Controller (Kc = 1)	**K_c = 0.01**	**K_c = 0.01, τ_I = 40s (I = 0.00025)**
2	1	0.5	1-500s	4501-5000s	9001-9500s
2	10	0.5	501-1000s	5001-5500s	9501-10000s
2	10	10	1001-1500s	5501-6000s	10001-10500s
5	1	0.5	1501-2000s	6001-6500s	10501-11000s
5	10	0.5	2001-2500s,	6501-7000s	11001-11500s
5	10	10	2501-3000s	7001-7500s	11501-12000s
10	1	0.5	3001-3500s	7501-8000s	12001-12500s
10	10	0.5	3501-4000s	8001-8500s	12501-13000s
10	10	10	4001-4500s	8501-9000s	13001-13500s

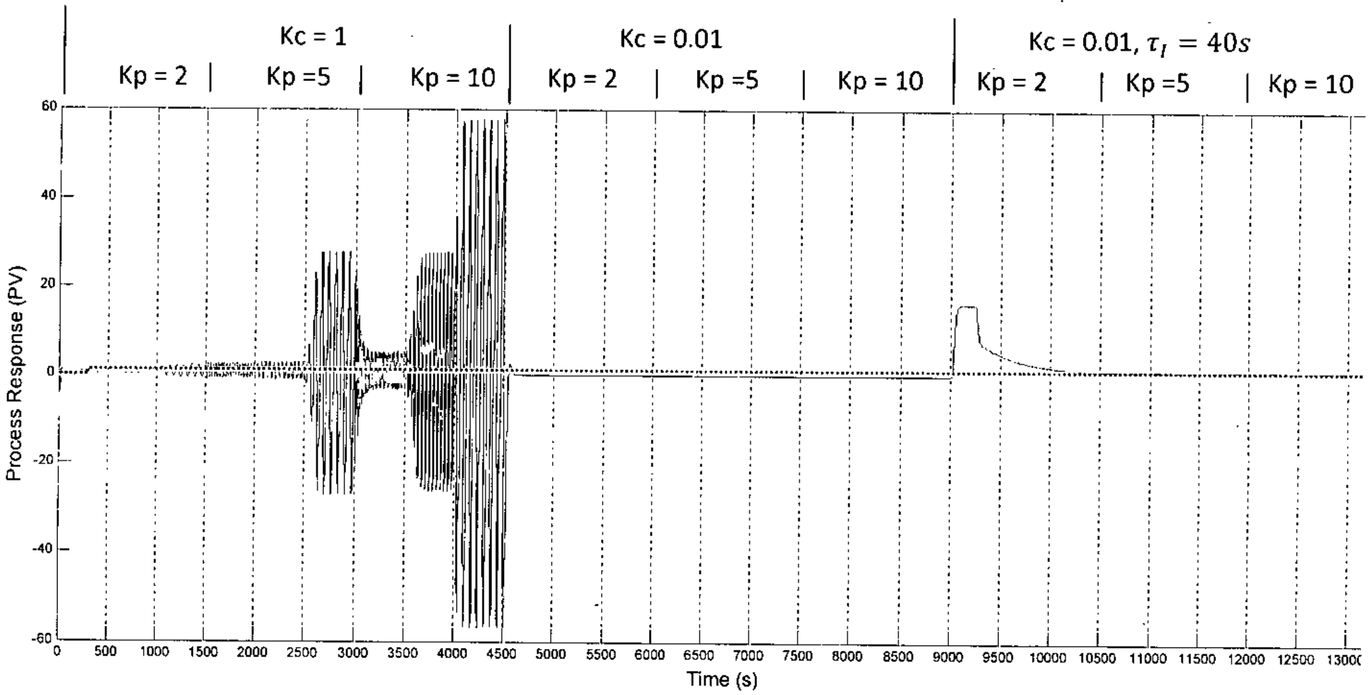


Figure 3.24. Response of the process for the Simulation Block of Figure 3.21 to check the effect of low integral action. Here, dotted line is the desired process output (setpoint). Solid black line is the simulated process output.The Integral action starts at time = 9000s.

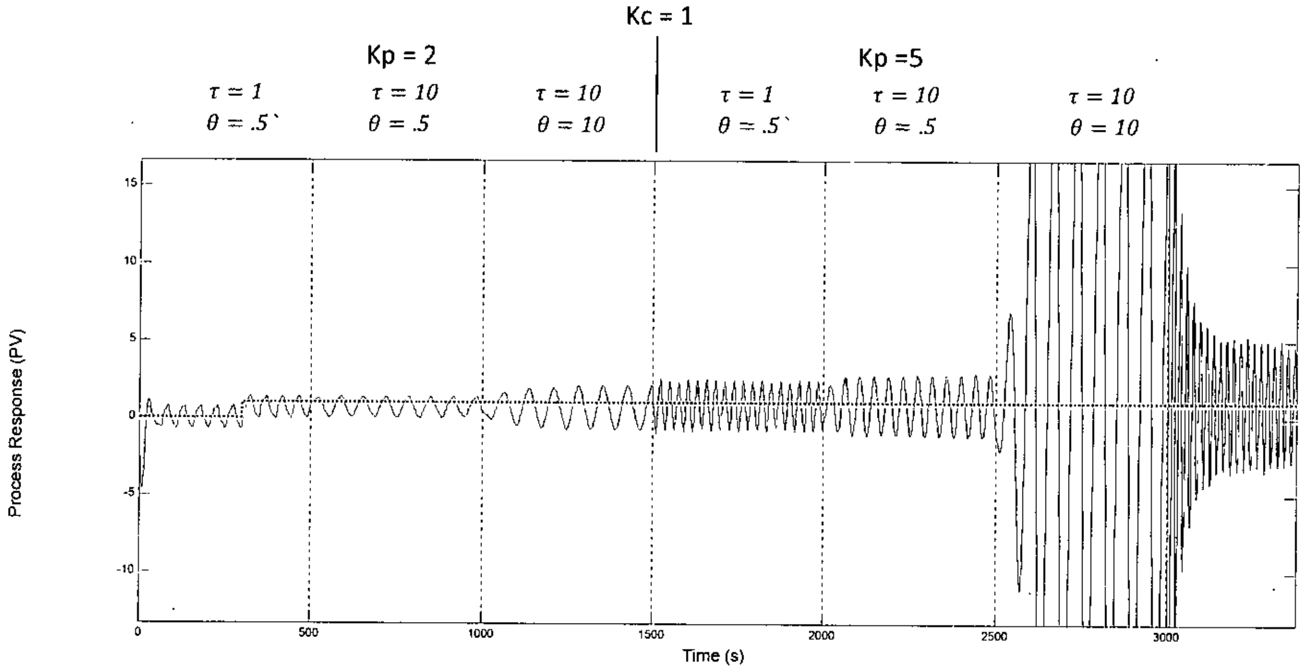


Figure 3.24a. Enlarged view of the initial 3000 seconds of Figure 3.24.

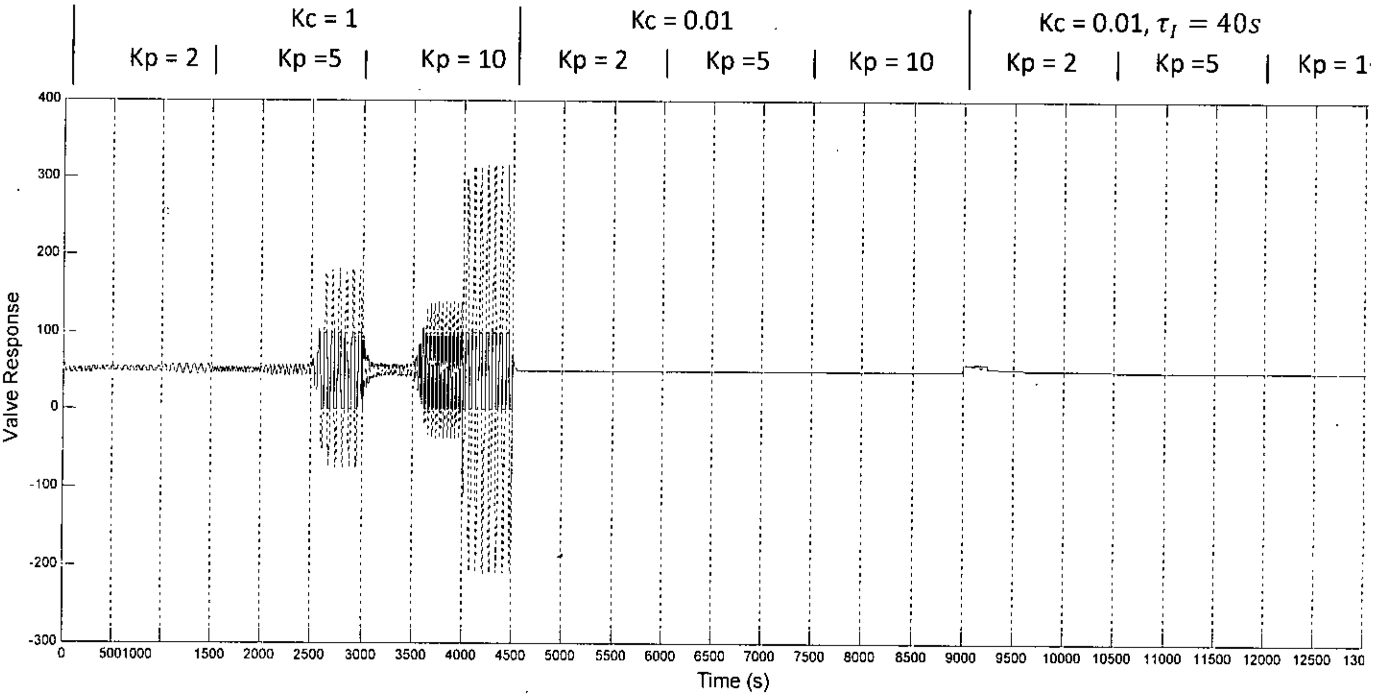


Figure 3.25. Simulated response of valve stem for the Simulation Block of Figure 3.21to check the effect of low integral action. The Integral action starts at time = 9000s. The dotted line indicates the input to the valve and solid line indicates the valve stem response.

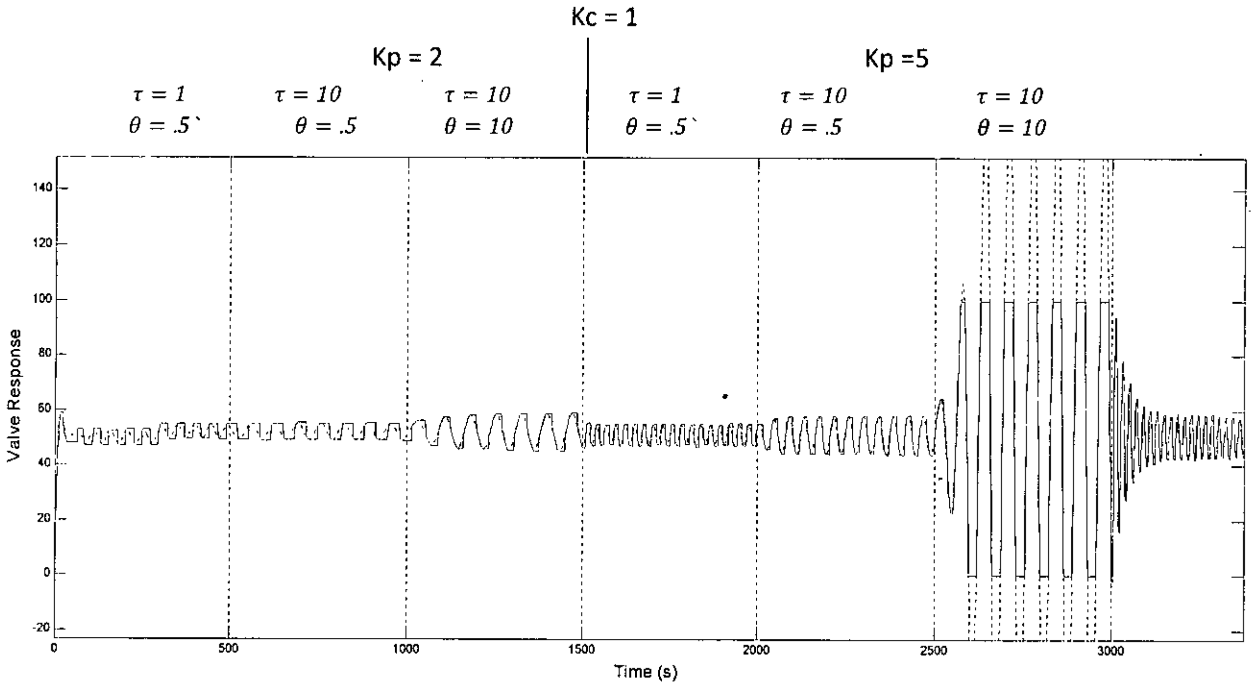


Figure 3.25a. Enlarged view of the initial 3000 seconds of Figure 3.25.

Figure 3.24 shows the response of different SOPTD processes while applying high integral time (>100s). The first 9000s is similar to Figure 3.22. After 9000s, the integral action was kicked off and it took about 1300s to reach the set point after an overshoot of about 400. Here, it is seen that the process oscillated for low Kp (even when Kp = 2) with Kc =1. But when lower Kc is applied the oscillation is nullified with the cost of some offset.

Figure 3.25 shows the simulated response of the valve while adding high integral time. Here, it is seen that adding the high integral part dose make the valve oscillatory again.

3.4 Guidelines for Efficient Tuning of PID Controller to Handle Stiction

From the outcome of this study, a guideline of controller tuning for a SOPTD process suffering from stiction can now be proposed.

Step 1 – Select a proportional only controller with a proportional gain (Kc) 0.01 if the process gain value is in between 2 to 50. If the process gain value is lower than 2, choose a higher value of Kc even in the order of 1. For the lower end of the process gain value higher value than 0.01 of Kc also can be used. But for saving the time it is recommended to choose 0.01.

Step 2 – Observe the process response with this proportional controller. If the amount of offset is beyond the tolerance limit, introduce very high value of integral time (τ_I). For a safe tuning process, start choosing τ_I from 100s, and if still the offset remains, gradually lower the τ_I. But it should be kept in mind that low τ_I can introduce the oscillation again. The operator has to optimize between the offset removal and oscillation caused by integral effect.

Step 3 – Since the simulation results shows that the derivative part has no effect on stiction, if the other part of the process requires introducing some derivative action, the operator can introduce it at this stage.

3.5 Conclusion

In this chapter, it is found that proper tuning of PID controller can handle stiction effectively. Initial investigation of this study indicated that integral part has very adverse effect on stiction and derivative part has very little or almost no effect on stiction and proper choice of a proportional only controller can handle stiction very effectively. An empirical correlation was developed for the calculation of controller gain varying with the process parameters of a SOPTD process (like process gain, time constant and time delay).

For this purpose 650 different combinations of Kc vs. Kp, 650 different combinations of Kc vs. τ and 520 different combinations of Kc vs θ were analyzed with the offset tolerance limit of $\pm 30\%$ to choose a better controller gain (Kc). Three different relations were found in this procedure. According to this method, the minimum of these three values will be used in a single case. The proposed method works well for SOPTD process with Kp upto 10 in presence of small time delay (in the range of 0.5). For very low value of Kp, higher value of Kc is required. So, SOPTD with lower gain or FOPTD should be handled with higher Kc.

To increase the range of applicability of the PID controller SOPTDs with higher Kp and time delay were simulated with very low value of Kc. It is found that Kc around 0.01 can handle process as the high gains (Kp = 50) and large delay (θ = 10). But since, offset is an inherent part of the Proportional only controller in this method there will be always be some offset. For the industry application this offset should be reduced and good set point tracking is necessary. The idea behind introducing the integral controller was to remove this offset. That is why it was tried to handle this offset problem by introducing high integral time (≥40s). Figure 3.24 shows that integral time with 40 seconds help the SOPTDs with stiction to track the set point without the oscillation problem.

At last a guideline was proposed for efficient tuning of the PID controller to handle stiction. This guideline will work as a starting point to tune the PID controller in presence of stiction.

Chapter 4

Developing an Inverse Stiction Model and Revisiting Dither

In the previous chapter, it was shown by simulation that stiction can be handled well by using PID controller with very low proportional gain and high integral time. The proposed correlation also worked well until a combination of very high gain and delay appeared. But in that method the process model is required as a priori. Since there are well established methods for detection and quantification of stiction, an inverse stiction model can be derived with help of the prior knowledge of the quantified stiction. In this chapter an attempt was made to develop an inverse stiction method by using the stiction model of [16]. At the last part of this chapter an alternative method named as 'dither' (proposed by [13]) was re-explored.

4.1 Inverse Stiction Model Approach

The inverse of a non-linearity produces a signal such that when that signal passes through the non-linear transfer function; their combined effect will nullify the nonlinearity. In mathematical formulation, if u is our desired signal and a non-linearity is present in the process such N, then inverse (NI) of this non-linearity will be such that N(NI(u)) = u....................(4.1).

From equation 4.1, it is clear that the inverse of the non-linearity N, produces such an output v from the input (u) to the inverse mechanism (NI) such that the effect of not-linearity (N) perfectly cancels out [18].

This can be further explained with the help of diagram as follows –

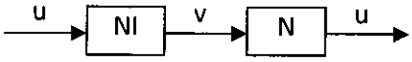


Figure 4.1. Inverse signal, here, v = NI(u).

In this study, an attempt was made to develop an inverse stiction module which will completely nullify the effect of stiction. Though another attempt of inverse stiction was made by [19] in presence of saturation, in this study it was tried to produce an exactly inverse signal of sticky valve using the stiction model by [16] in absence of saturation. Then this signal will be added to the output of the valve and thus the cumulative result will be a totally oscillation free signal. To apply this method, exact quantification of stiction is necessary.

4.1.1 Open Loop Test

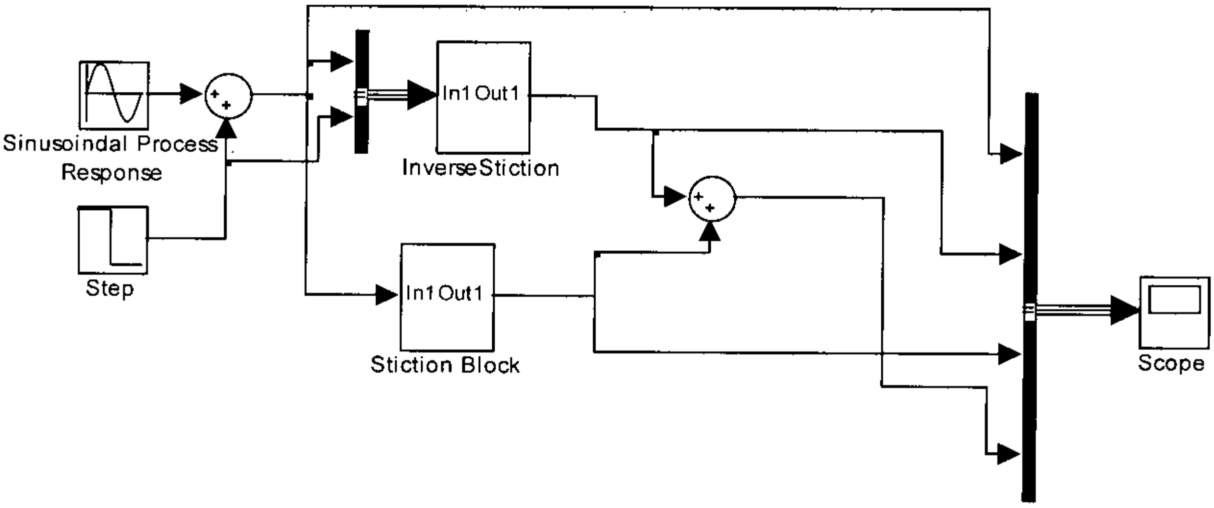


Figure 4.2. *Simulation Block diagram for the proposed parallel Inverse Stiction Method in Open Loop.*

Figure 4.2 is the representation of the proposed inverse stiction method for open loop test. Since, the output signal from the valve (in this case stiction Block) is added with the inverse stiction signal and their combined effect is nullification of limit cycle, it has been termed as 'Parallel Inverse Stiction Method'.

Figure 4.3 shows the effect of this inverse stiction method. From this graph, it is seen that the process takes the stiction free signal to track the setpoint as if it is getting it directly from the controller without the interference from a sticky valve. In this case, process input was given as a sinusoidal signal of amplitude 1 and frequency 0.05. Set point was changed from 6mA to 4 mA after 300 seconds. The combined effect shows that that it has tracked the set point quite efficiently without any effect of stiction i.e. the inverse Stiction model has produced exactly the inverse of the response of the sticky valve.

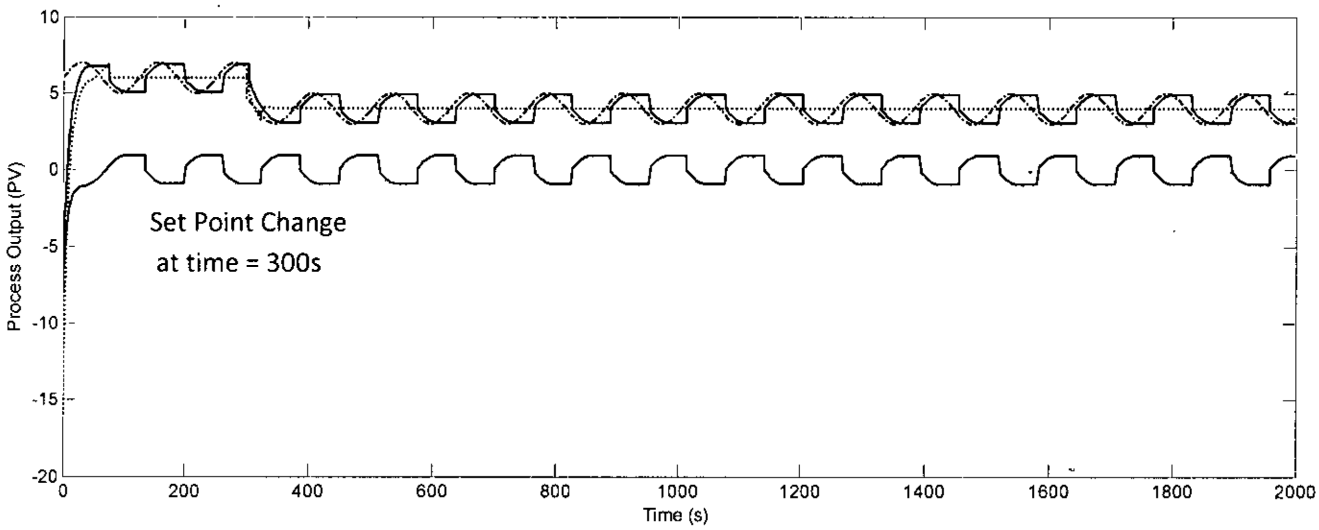


Figure 4.3. *Responses of the open Parallel Inverse Stiction Method. Here, the alternate dash(- dotted) line is the process output (input to the inverse Stiction and Stiction block), the lower solid line indicates the inverse stiction signal from the inverse Stiction block to this input, the upper solid line indicates the response of the sticky valve and the dash line (----) indicates the combined effect of the inverse Stiction signal and Sticky valve. This is the process input which exactly tracks the set point with minimal error.*

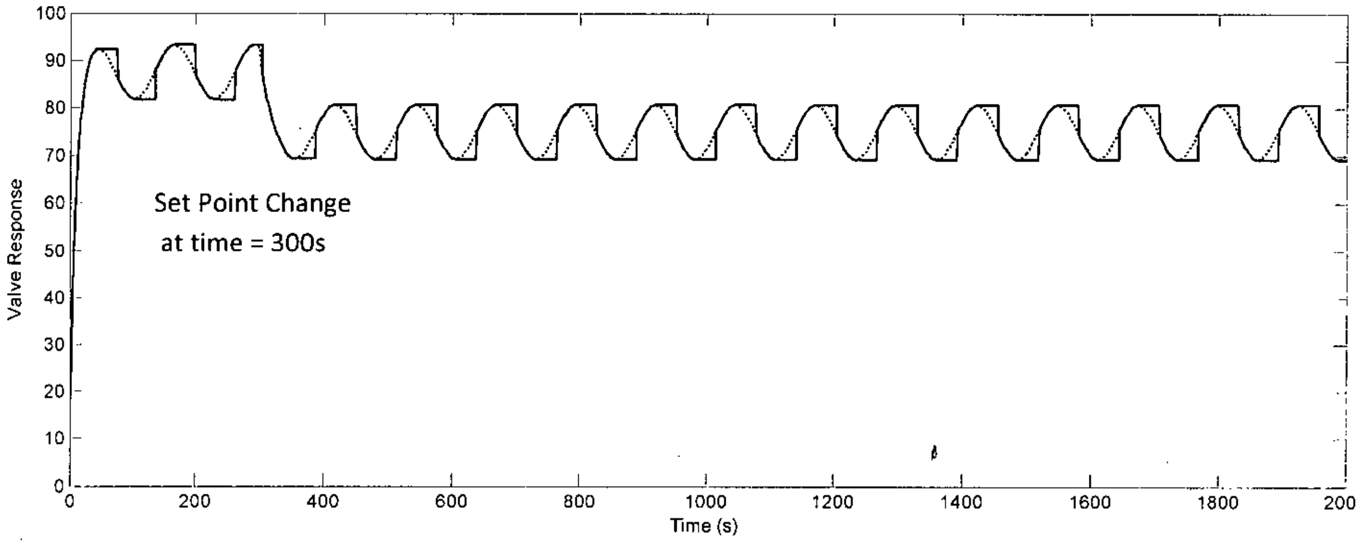


Figure 4.4. *Simulated Response of the valve stem for the proposed parallel Inverse Stiction Method in open loop. Here, the solid line indicates the stem movement. The dotted line indicates the input to the valve. Setpoint was changed after* 300s.

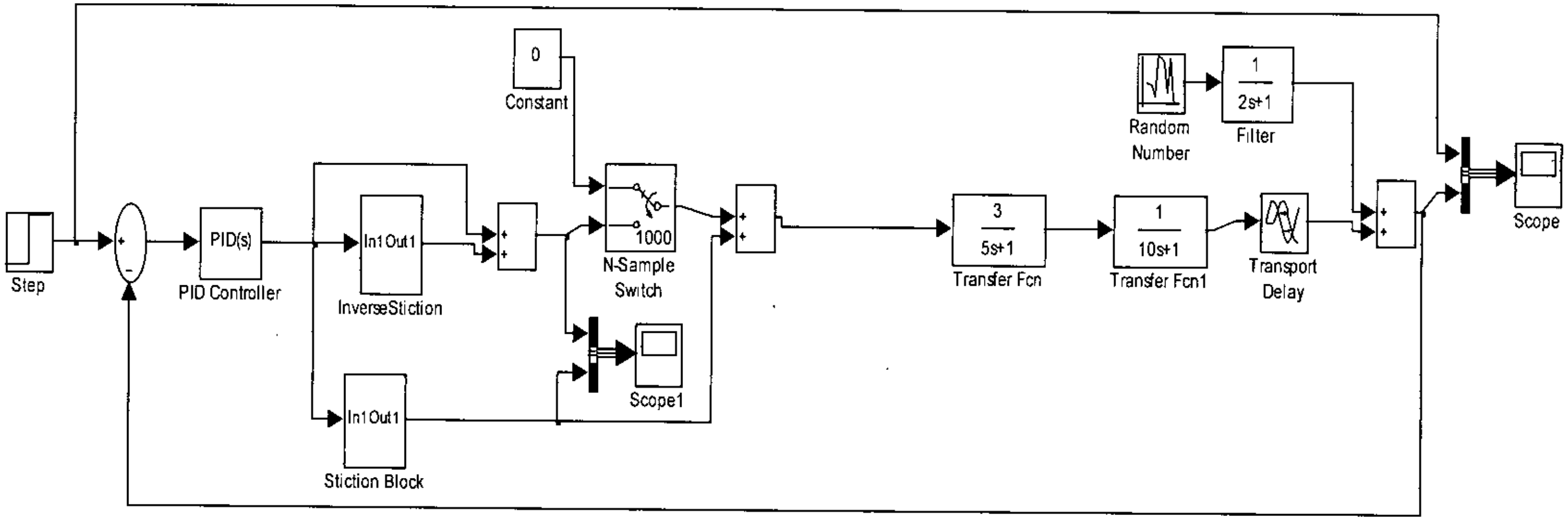


Figure 4.5. Simulation Block diagram for the proposed parallel Inverse Stiction Method in Close Loop

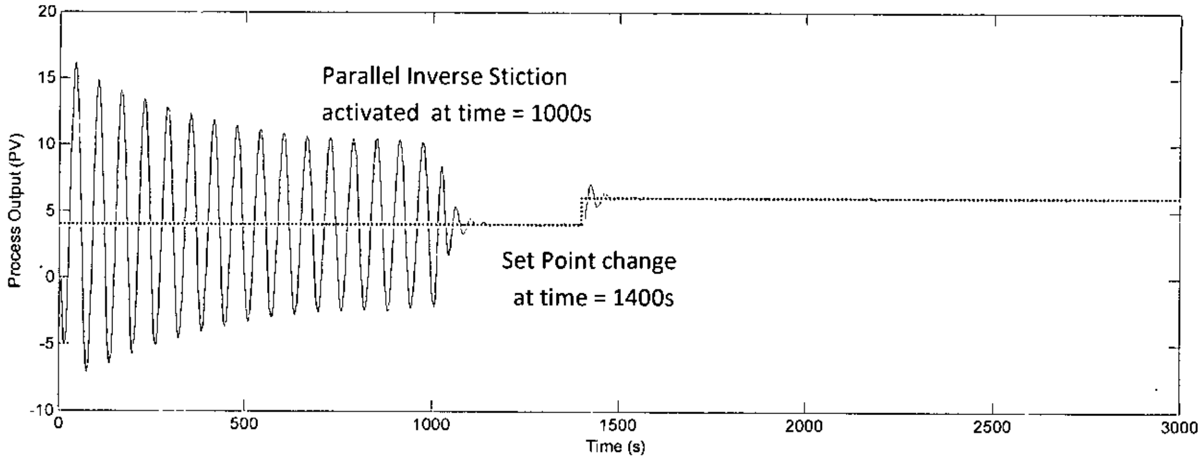


Figure 4.6. Close Loop Response of the rest of the process other than the valve while applying the proposed parallel inverse stiction method. Here, the dotted is the desired and solid line is the actual process response.

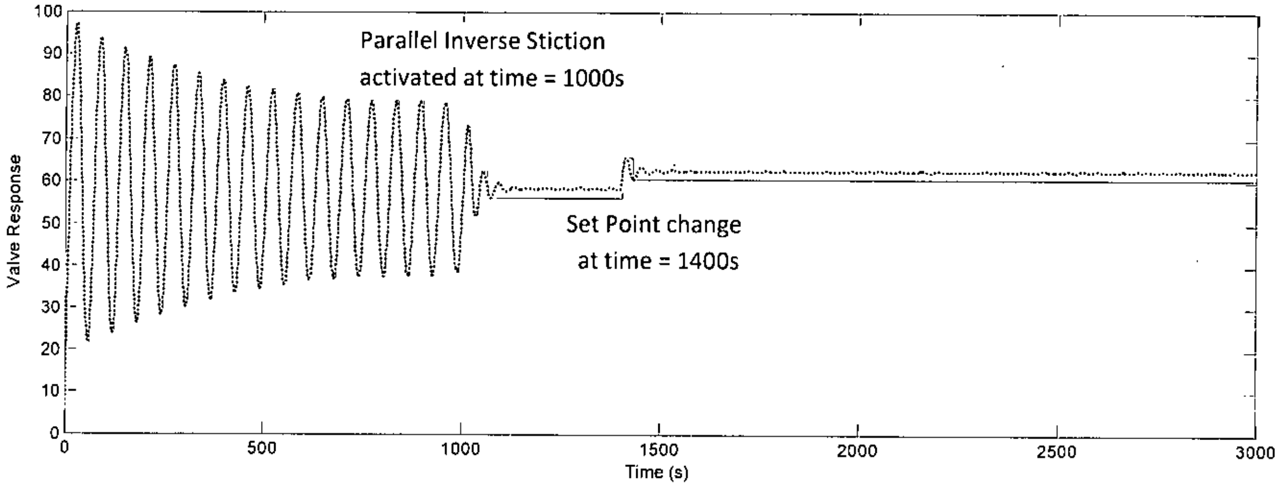


Figure 4.7. Simulated Response of the Valve Stem for the proposed Parallel Inverse Stiction Method in Close Loop in presence of Disturbance. Here, the dotted line indicates the controller output (valve input), solid line indicates the Valve stem movement. From this figure it is clear that the stem moves more steadily after the inverse stiction was activated. A slight overshoot occurs when the step was changed at 1000s.

4.1.2 Closed loop Test.

A SOPTD process was chosen for this purpose $(\frac{3}{5s+1} \times \frac{1}{10s+1} \times e^{-5s})$. The closed loop simulation block diagram is shown in Figure 4.5. Figure 4.6 describes the response of the process when the model is applied in closed loop. In case of closed loop, a step change was occurred after time 1400s from 4 mA to 5 mA. The inverse stiction block was activated after time 1000s. This figure also shows that this method can track set point change. This method can also minimize the effect of disturbances. Figure 4.7 is the simulated response of the valve stem in closed loop block. The PID controller parameters were selected as calculated from the IMC method for the SOPTD process (Controller gain = 0.6, Integral time = 15s , Derivative time = 3.33s).

However, the accuracy of this method depends on exact quantification of the amount of stiction. This method does not relief the valve from its sticky behavior, but it just compensates its effect toward the rest of the part of the process. The major drawback of this method is that valve is also a part of the process and adding a signal with the valve output has some practical limitations.

4.1.3 Inverse Stiction in Series

Figure 4.8 shows the inside of the inverse stiction block. Here, the two parameter stiction model by [16] was used to predict the response of the sticky valve and Matlab function produces the inverse signal that will go through the sticky valve. The Matlab function in this case is quite different from the Matlab function of the inverse stiction block for parallel combination. In that case, an opposite signal of the sticky valve response was produced, which will nullify the effect of stiction when in combination with the sticky valve.

In this case it was tried to develop an actual inverse stiction i.e. the inverse signal, that will be applied in series with the sticky valve and since in case of series combinations, the product of the transfer functions of the inverse and the nonlinearity is 1 (equation 4.1), so that the effect of stiction i.e. the limit cycle will be completely nullified. Here, the Matlab function takes the input from the PID controller and makes it negatively inverse i.e. $\frac{-1}{output\ from\ the\ PID\ controller} + \frac{Setpoint}{Process\ Gain}$. This is the input to the second part of inverse stiction block i.e. to the two parameter stiction model by [16]. This stiction block now will produce the exact inverse response for the sticky valve provided that the stiction of the sticky valve is properly quantified and this quantified stiction is incorporated in this stiction block.

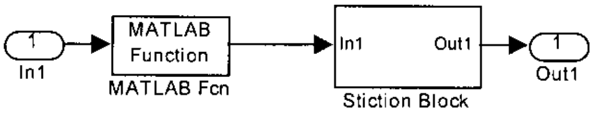


Figure 4.8. Inside of the Inverse Stiction Model

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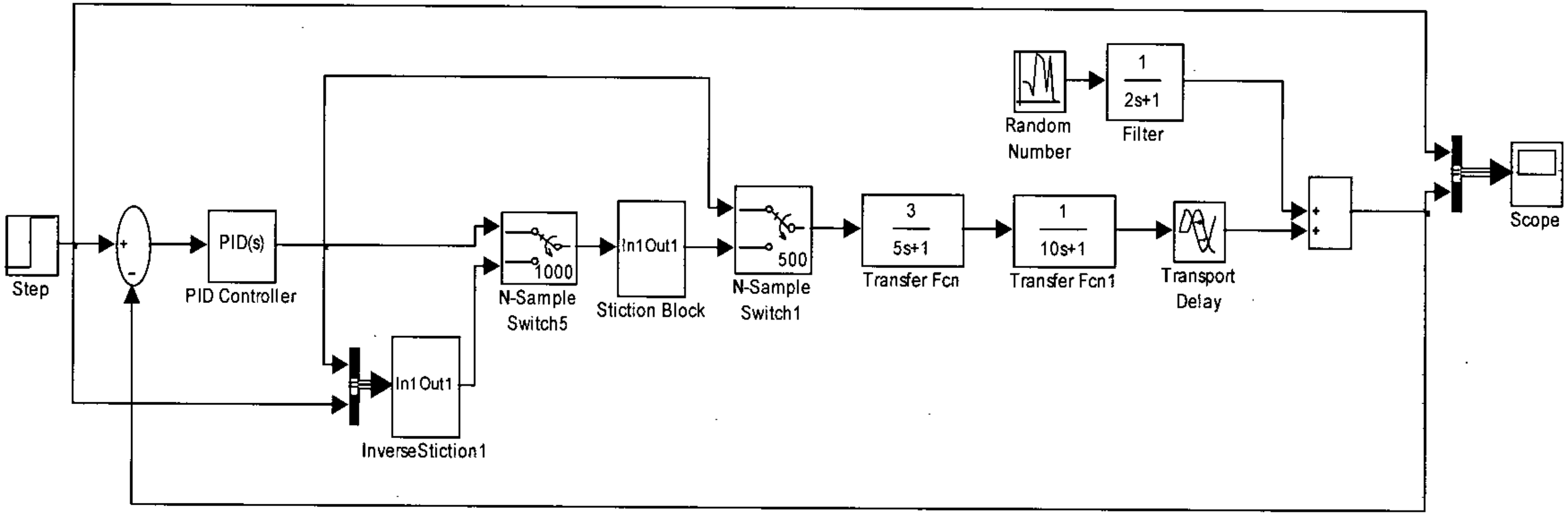

Figure 4.9. *Simulation Block diagram for the proposed Inverse Stiction Method in Series Combination with the Sticky valve in Close Loop*

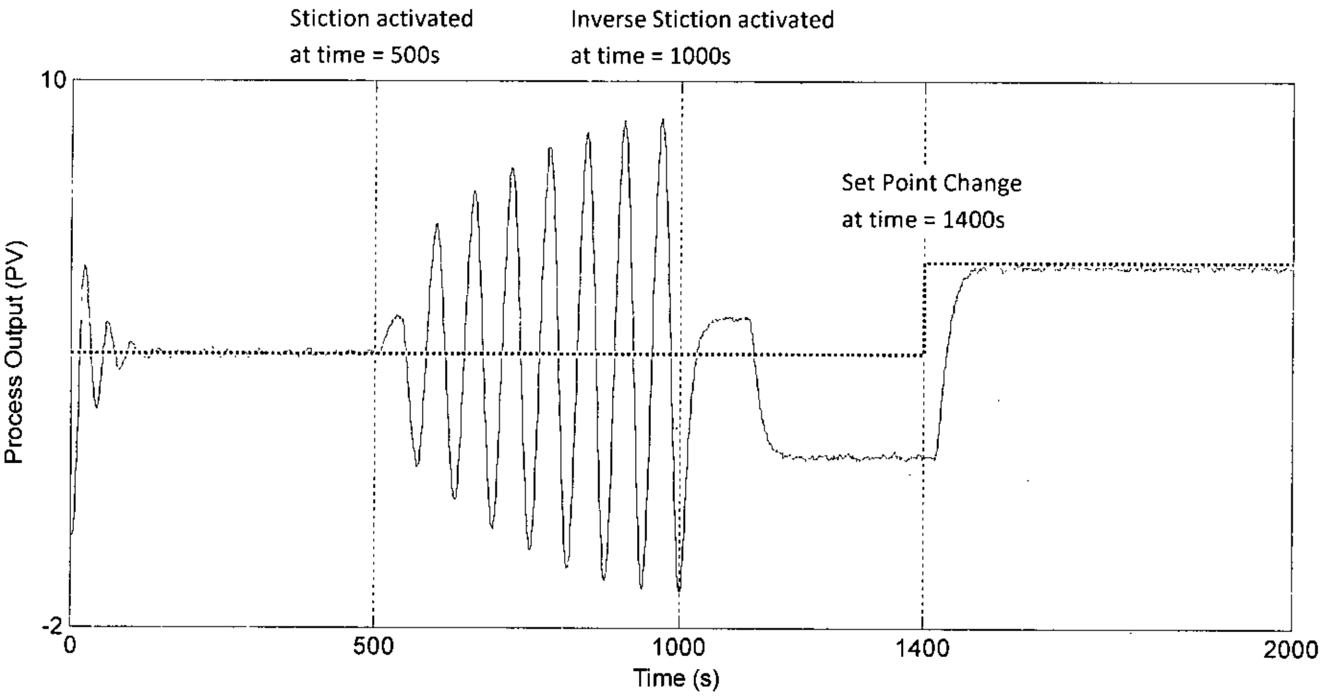

Figure 4.10. *Response of the process as shown by Figure 4.9. Here, 1st 500s only the IMC PID controller was activated, Stiction was activated on* 500s*. At* 1000s *inverse stiction was activated. A set point change occurred on* 1400s*. The dotted line indicates the desired process output(set point). The solid line shows the simulated process response.*

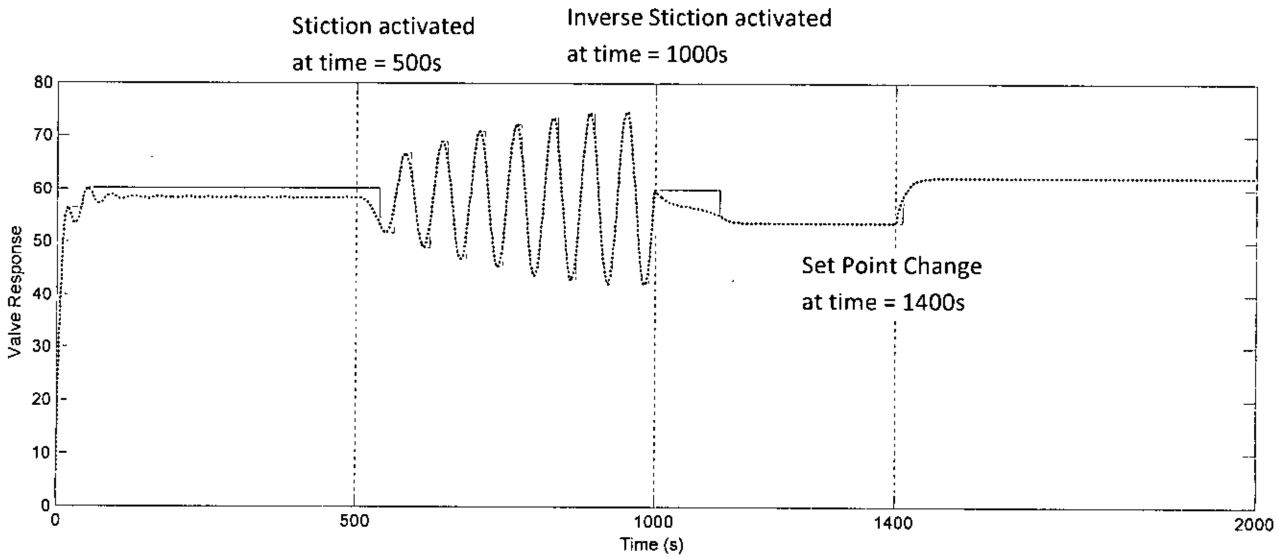

Figure 4.11. *Simulated Response of the Valve stem for the Simulink model as shown by Figure 4.9. The solid line indicates the stem movement. The Dotted line indicates Controller output. The faded color line indicates the models saturation values. For time* 500-1000s *,the stem movement shows a clear evidence of Stiction. For time* 1000-2000s*, when inverse stiction was applied in series the limit cycle in stem movement is nullified.*

The Simulink model for this purpose was devised as in Figure 4.9. Here, th e process was $\frac{3}{5s+1} \times \frac{1}{10s+1} \times e^{-5s}$. For the first 500s the process was simulated without the effect of stiction. At this period only the IMC controller was activated. After 500s , soft stiction as defined by the two parameter stiction model by [16] with S=5, J=5 was activated and after 1000s the proposed inverse stiction model was activated. A set point change is also introduced after time 1400s to see the effect of set point change on the proposed inverse stiction method. Here, a disturbance was also added to check the effect of disturbance.

Figure 4.10 is the process response when this inverse stiction method was applied on the process. Here, it is seen that the PID controller which was tuned by the IMC method tracks the set point satisfactorily until the there was any stiction problem. But at 500s when soft stiction was applied the process starts oscillating. And then when, the inverse stiction was applied in series, the oscillation problem is removed though there is some offset in the process response. A set point change occurs at time t = 1400s, and it shows that the inverse stiction method can track the set point though there is some sort of offset problem.

Figure 4.11 shows the simulated valve stem movement for this simulation. From this figure it is also evident that the valve moves abruptly when the Soft-Stiction was activated at time 500s. But the valve movement was rather stable when there is no effect of stiction i.e. from 0-500s. Again, the valve became stable when inverse stiction was applied.

4.2 Compensation Using Dither

4.2.1 Dither

From literature point of view the word "Dither" is a British colloquialism for "undecidedness", or "wishy washiness", i.e. somewhat related to hesitation or oscillation or vibration etc [20].

From engineering point of view dither means to create an oscillation to achieve a certain goal. It has a great importance in sound engineering [20]. But dither can be a useful tool to handle stiction. In the year 1940, dither was first time used in combating stiction. The British naval air fleet was having problems with their navigation systems which were huge mechanisms full of cranks, gears and cogs (teeth of gear). These cogs were chatter and stick i.e. did not move very smoothly and hence it was very difficult to calibrate. But when the airplanes were in the air, the problems seemed to go away. At that time it was predicted that the vibration of the plane's engine, would have eased the sticky condition of cogs. Based on this assumption, the British installed small motors on all of their navigation systems just to help vibrate the mechanisms on the ground and astoundingly it worked well and those motors helped the rigid mechanism to operate more fluidly.

4.2.2 Dither in Process Control

Though dither is being used in servo systems frequently to remove the effect of stiction [13], it cannot be directly used in pneumatic control valves, because the pneumatic valves have much slower dynamics than the servo systems [4]. In this study, it was tried to apply the technique of dither in pneumatic valve. The idea behind this test was that to keep the valve stem vibrating continuously. This can be done in two ways –

1) Physical method as in the original dithering technique, i.e. attaching a small motor around the valve stem to keep it continuously vibrating all the time.

2) By keeping the stem continuously moving by adding a low amplitude low frequency sinusoidal signal with the controller signal, that will make the diaphragm of the valve continuously vibrating and hence the stem. But in this case the pressure on the diaphragm should be sufficient enough to move the stem and spring system continuously.

In this study the second option was simulated by Simulink. Here, the sticky behavior of valve was simulated by using the stiction model of [16]. A SOPTD process was selected as before. A proportional only controller with proportional gain 1 was used. After 1200 second the dither signal was activated (Figure 4.12). Amplitude and Frequency of the dither signal was chosen by trial and error basis by a simple Matlab code. The SOPTD process was $\frac{2}{s+1} \times \frac{1}{10s+1} \times e^{-0.5s}$.

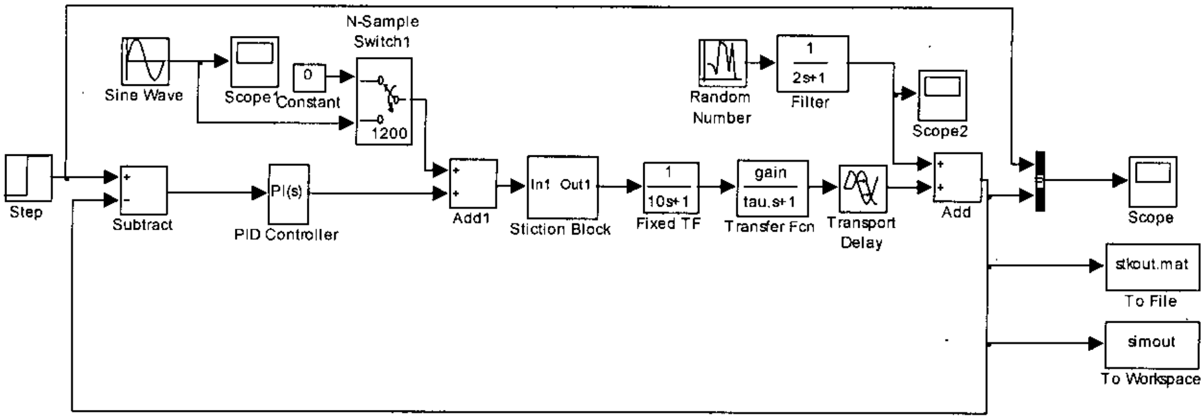

Figure 4.12. Simulation Block diagram for simulating the effect of Dither.

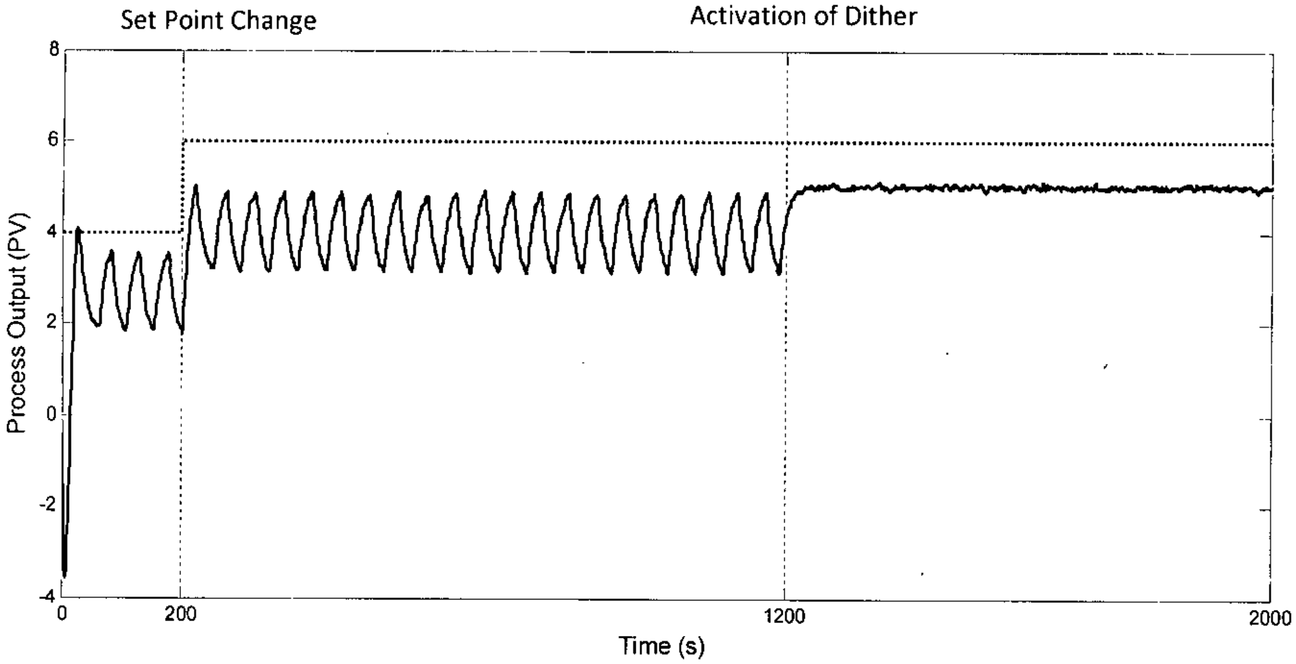

Figure 4.13. *Effect of Dither signal on Stiction. Here, setpoint was changed from 4 to 6 mA after* 200s,*Proportional gain was 1 throughout the simulation, Dither was activated after* 1200s. *The Oscillation becomes negligible at that moment. Here a sine wave of amplitude 1 and frequency* 0.54 *rad/s was used as the Dither signal. The amplitude and frequency were selected by a trial and error basis by a simple Matlab code.*

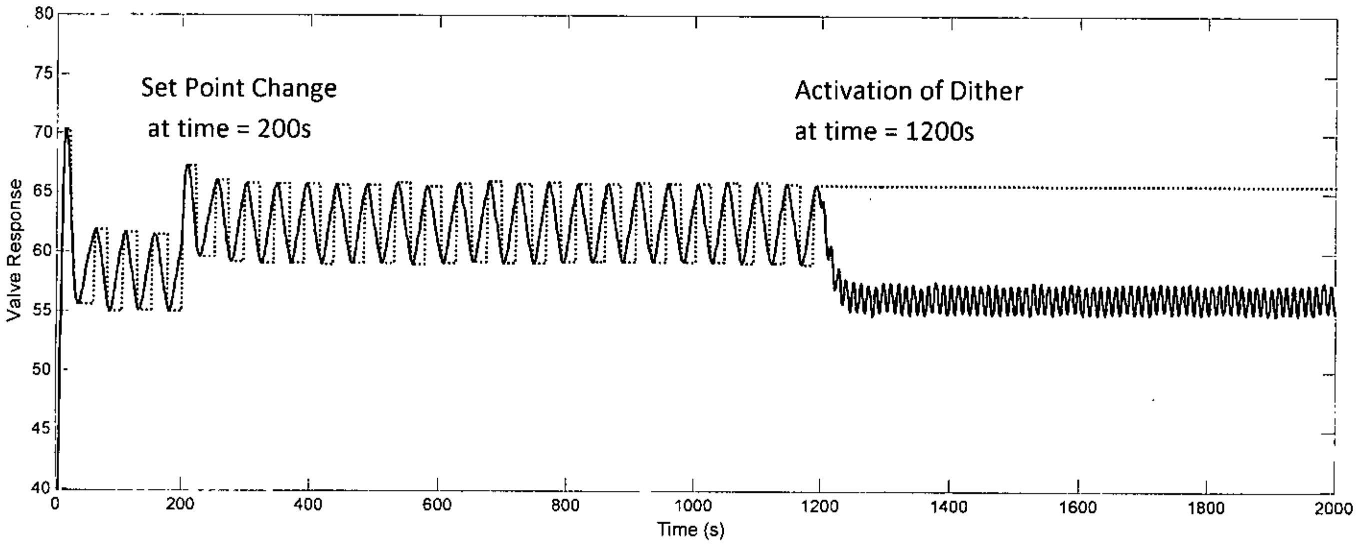

Figure 4.14. *Simulated response of the Valve Stem to show the effect of Dither signal as applied in figure* 4.12. *Here the valve stem becomes fixed after Dither is signal is applied after* 1200*sec. Here, the dotted line indicates the stem movement. Solid line indicates the valve input.*

A trial and error procedure was followed. In the trial error procedure the best result for the process under study was observed when amplitude was 1 and frequency was 0.54. Both are quite high than expected (Figure 4.13). If the simulated valve stem movement is observed as seen in Figure 4.14, it is seen that the valve stem became stationary after the dither is activated (at time 1200s). Though, it has nullified the limit cycle behavior of the stem, but it introduced some offset and stationary condition of the valve stem is very suspicious because the stem might have stuck at that position.

So, the author suggests further investigation in both the possible ways of applying dither in pneumatic valve. Due to time constraint, further investigation is beyond the scope of this study.

4.3 Conclusion

In this chapter an alternative inverse stiction method is introduced by using the two parameter stiction model by [16]. The inverse stiction (in series w ith the sticky valve) produces non-oscillatory response of the process with the cost of offset. The parallel inverse stiction model tracks the set point without any oscillation and offset, though parallel inverse stiction method has some practical limitation. Future work can be done to improve these two methods. Though, the soft dither method did not work well it can be interesting to check the effect of physical dither by introducing continuous vibration in the valve stem and packing region with help of an external motor.

Chapter 5

Conclusions and Recommendations for Future Work

In this chapter findings from the previous chapters are summarized. Recommendations for future work are also enlisted at the later part of this chapter.

5.1 Conclusions

The main results of this study can be summarized as follows:

1. Integral part has adverse effect on stiction
2. Derivative part has almost no effect on stiction.
3. Low value of proportional only controller can handle this stiction problem efficiently with the cost of some fixed offset. This study was based on SOPTD processes since this type of process gives a sustainable oscillation under the effect of stiction. SOPTD with very low process gain (<1) requires higher value of proportional gain (in the range of 1). But higher process gain requires lower proportional gain.
4. Process gain has the strongest effect on proportional gain. Time constant has the weakest effect.
5. The empirical relation proposed in this study requires the knowledge of the process in priori. It works well for processes with low process gain and small time delay.
6. For process gain larger than 1 and up to 50, a very low proportional gain in the range of 0.01 works well to reduce the oscillation. However, since an offset is an inherent property of proportional only controller, there will always be some offset.
7. To reduce this offset problem, it was tried to introduce high integral time (starting from 100s) constant and it shows that adding this high integral time constant improves the set point tracking criteria.
8. A guideline for efficient tuning of the PID controller in presence of stiction is also proposed for SOPTD processes. This guideline will work as a starting point while tuning PID controller in presence of a sticky valve in the control loop.
9. Alternative inverse stiction models which will work both in series and parallel with the sticky valve have developed using the two parameter stiction model by [16].

10. Actually, inverse stiction should work in series with the sticky valve. In that sense, the proposed inverse stiction method worked well to nullify the effect of oscillation caused by stiction. Though, in some cases it might produce some offset, but it works well in presence of disturbances also.
11. Finally, dither method was re-explored which implies that applying dither to pneumatic valve is not feasible due to the fact that the pneumatic valve has slower dynamics than the dither.

5.2 Suggestions for Further Work

- The performance of the proposed correlation for the PID controller for SOPTD processes might be investigated in pilot plant and by using process plant data. Further investigation is required to remove the offset problem with more efficiency.
- The guideline for tuning the PID controller to handle stiction problem should also be tested in a pilot plant.
- The developed inverse stiction method shows good performance to reduce the oscillation caused by stiction. However, sometimes it shows some offset in certain conditions. More robust inverse stiction method should be developed. The performance of the inverse stiction method should be evaluated through pilot plant experimentation before applying it to the process plant.
- Though applying a continuous vibration to the valve diaphragm by adding a sinusoidal signal method did not work, future work can be done to examine the effect of physical dither by introducing continuous vibration in the valve stem and packing region with the help of an external motor.

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Appendix A

Table A.1 : Data for deriving the best Controller Gain vs. Process Gain Ratio for 30 % tolerance of Offset. Here set point was 1

Controller Gain, Kc	**Process Gain, Kp**	**Ratio (Kc/Kp)**	**Amplitude of Process Oscillation between 0.7 & 1.3**
0.05	3.5	0.014286	0.73931
0.05	4	0.0125	0.959598
0.05	4.5	0.011111	1.215639
0.1	2.5	0.04	0.906865
0.1	3	0.033333	1.274564
0.15	2	0.075	0.963661
0.2	1.5	0.133333	0.80821
0.25	1.5	0.166667	1.022295
0.3	1.5	0.2	1.235854
0.35	1	0.35	0.759241
0.4	1	0.4	0.865521
0.65	1.5	0.433333	1.159335
0.75	1.5	0.5	1.202
0.8	1.5	0.533333	1.208113
0.85	1.5	0.566667	1.236846
0.9	1.5	0.6	1.272411
0.95	1	0.95	0.958136
1	1	1	0.978809
2	0.5	4	0.794422
2	1	2	1.208288
3	0.5	6	0.879545
4	0.5	8	0.958468
5	0.5	10	1.085757
Average Ratio = 1.566068			**Avg. Amplitude = 1.030125**

Table A.2 : Data for deriving the best Controller Gain vs. Process Gain Ratio for 50 % tolerance of Offset. Here set point was 1.

Controller Gain, Kc	**Process Gain, Kp**	**Ratio (Kc/Kp)**	**Amplitude of Process Oscillation between 0.5 & 1.5**
0.05	3	0.016667	0.55464
0.05	3.5	0.014286	0.73931
0.05	4	0.0125	0.959598
0.05	4.5	0.011111	1.215639
0.1	2	0.05	0.613199
0.1	2.5	0.04	0.906865
0.1	3	0.033333	1.274564
0.15	1.5	0.1	0.596063
0.15	2	0.075	0.963661
0.15	2.5	0.06	1.44153
0.2	1.5	0.133333	0.80821
0.2	2	0.1	1.32164
0.25	1	0.25	0.545877
0.25	1.5	0.166667	1.022295
0.3	1	0.3	0.652759
0.3	1.5	0.2	1.235854
0.35	1	0.35	0.759241
0.4	1	0.4	0.865521
0.5	2	0.25	1.36919
0.55	2	0.275	1.392829
0.6	2	0.3	1.417984
0.65	0.5	1.3	0.532937
0.65	1.5	0.433333	1.159335
0.65	2	0.325	1.451613
0.7	0.5	1.4	0.56787
0.7	2	0.35	1.467994
0.75	0.5	1.5	0.60306
0.75	1.5	0.5	1.202
0.8	0.5	1.6	0.63729
0.8	1.5	0.533333	1.208113
0.85	0.5	1.7	0.673351
0.85	1.5	0.566667	1.236846
0.9	1.5	0.6	1.272411
0.95	1	0.95	0.958136
0.95	1.5	0.633333	1.315595
1	1	1	0.978809
1	1.5	0.666667	1.305304

2	0.5	4	0.794422
2	1	2	1.208288
3	0.5	6	0.879545
4	0.5	8	0.958468
5	0.5	10	1.085757
Average Ratio = 1.12372			**Avg. Amplitude = 1.003657**

Table A.3 : Data for deriving the best Controller Gain vs. Process Gain Ratio for 20 % tolerance of Offset. Here set point was 1.

Controller Gain, Kc	**Process Gain, Kp**	**Ratio (Kc/Kp)**	**Amplitude of Process Oscillation between 0.8 & 1.2**
0.05	4	0.0125	0.959598
0.1	2.5	0.04	0.906865
0.15	2	0.075	0.963661
0.2	1.5	0.133333	0.80821
0.25	1.5	0.166667	1.022295
0.4	1	0.4	0.865521
0.65	1.5	0.433333	1.159335
0.95	1	0.95	0.958136
1	1	1	0.978809
3	0.5	6	0.879545
4	0.5	8	0.958468
5	0.5	10	1.085757
Average Ratio = 2.267569			**Avg. Amplitude = 0.962183**

Table A.4 : Data for deriving the best Controller Gain vs. Process Time Constant Ratio for 30 % tolerance of Offset. Here set point was 1.

Controller Gain, Kc	**Time Constant, τ**	**Ratio (Kc/ τ)**	**Amplitude of Process Oscillation between 0.7 & 1.3**
0.1	0.5	0.2	0.997589
0.1	1	0.1	1.035208
0.1	1.5	0.066667	1.076526
0.1	2	0.05	1.115777
0.1	2.5	0.04	1.151628
0.1	3	0.033333	1.183115
0.1	3.5	0.028571	1.211488
0.1	4	0.025	1.236453
0.1	4.5	0.022222	1.256505
0.1	5	0.02	1.274564
0.1	5.5	0.018182	1.289175
0.1	6	0.016667	1.299737
0.1	20	0.005	1.239769
0.1	30	0.003333	1.133716
0.1	40	0.0025	1.048753
0.1	50	0.002	0.977524
0.1	100	0.001	0.760715
0.15	100	0.0015	1.094186
1	100	0.01	1.295814
Average Ratio = 0.033999			**Avg. Amplitude = 1.14096**

Table A.5 : Data for deriving the best Controller Gain vs. Process Time Delay Ratio for 30 % tolerance of Offset. Here set point was 1.

Controller Gain,Kc	Time Delay,θ	Ratio(Kc/ θ)	Amplitude of Process Oscillation between 0.7 & 1.3
0.05	10	0.005	0.710122
0.1	0.5	0.2	0.955379
0.1	1	0.1	0.990649
0.1	1.5	0.066667	1.026298
0.1	2	0.05	1.062274
0.1	2.5	0.04	1.098097
0.1	3	0.033333	1.134118
0.1	3.5	0.028571	1.169318
0.1	4	0.025	1.20456
0.1	4.5	0.022222	1.239174
0.1	5	0.02	1.274564
Average Ratio = 0.053709			**Avg. Amplitude = 1.078596**