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Proportional Integral Derivative Controller based Multiple Dominant Pole-Placement for Controlling Integrating Processes

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ABSTRACT: Process integration is requiring in many industries. Proportional-integral-derivative controllers are being widely used for integrating of process. Optimization method, direct synthesis, stability analysis and Internal Model Control approaches are used to design Proportional-integral-derivative controller. For linear control systems, pole placement is a well-established design method of Proportional-integral-derivative controller. With a low-order feedback Proportional-integral-derivative controller cannot achieve arbitrary pole placement for a high-order or delay system. Dominant pole placement is partially or hopefully is bets option for higher order system.

In this paper, fourth-order dominant pole method have presented for tuning a Proportional-integral-derivative controller to integrating first order plus time delay processes. Simulations have carried out on integrating first-order plus time-delay processes. These simulations on integrating processes and a nonlinear air levitation system model is used validate the applicability and effectiveness of the proposed method. The efficiency of the proposed method has evaluated in terms of time response specifications for servo as well as regulatory applications. The recommended method is compared with the previously reported approaches in terms of integral square error, integral of absolute error, steady state error and total variance. It is found that the proposed method can be used to obtain non-oscillatory servo step responses. It is found that the performance of the proposed method is enhanced than existing system in terms of integral of square error, integral of absolute error, steady state error, total variance and time domain specifications.

KEYWORDS: Simulation, Genetic Algorithm, PID, Tuning,Integrating processes,Error

I. INTRODUCTION

Recently, integrating systems have become a hot topic in terms of automatic control. These types of systems have at least one pole at origin, which is considered a characterization of open loop instability. Integrating systems are not self-regulating, which implies that bounded inputs may result in unbounded outputs in the time domain. Because of this, controlling such processes is challenging task. Zeigler and Nichols [1] investigate the three primary control effects found in present-day instruments, assign practical values to each effect, analyze what adjustment each has on the final control, and supply a method for determining the optimum PID settings of each control effect. Wang and Cluett [2] extend the frequency domain PID controller design concept. Skogestad [3] has developed different analytical simple rules for tuning the PID controller that will provide good closed-loop performance. Dela Sen [4] has studied spectrum assignment properties that are associated with output feedback pole placement based controllers. It has commensurate point delays and is used for linear time-invariant systems that give a single output on a single input. For PID control systems, Qing Guo et al [5] propose two simple and modest approaches that can promise the power of the allocated two poles. Ahmad Ali and S. Majhi [6] offer guidelines for choosing the gain crossover frequency and slope of Nyquist curves to govern integrating processes. In addition, they provide analytical expressions that relate controller parameters to model parameters. K.G. Papadopoulos et al. [7] have proposed a symmetrical optimum criterion based control law that shows a significant improvement when considering disturbance rejection. Alfaro V. M. and Vilanova R. [8] propose a robust tuning based two degree freedom proportional integral controller and evaluate close loop performance. Using optimization methods, they used non oscillatory targets. They find that targets with non-oscillatory responses provide smoother output with improved servo control Nicoloas [9] has developed simplified analytical expressions for controller parameters by using Plant models with low order and pure integrators. The paper by Jin Q.B. and Q. Liu [10] provides an analytical approach for tuning PIDs. An analytical tuning of two-degree-of-freedom (2-Dof) PID controller using enhanced internal model control (IMC) on the basis of the robustness analyses.

M. Ajmeri and Ahmad Ali [11] have given excellent method for designing PID controller for integrating processes using direct synthesis method.

Anil Ch. and Padma Sree R. [12] have direct synthesis method with time delay used to design a PID controller for integrating systems. The filter is based on the characteristic equation of the integrating system and the PID controller. In this desired characteristic equation, multiple poles are positioned at similar desired locations. The tuning parameters are adjusted to achieve the desired strength. Tuning actions are often well-defined in terms of process parameters for many forms of integrating systems. This controller design technique can be applied to many transfer function models and nonlinear models. Kumar D.B. and Padma Sree R. [13] have applied IMC principles to design PID controllers. In this proposal, IMC filters (Q) have been used. In the IMC controller, the order of the denominator is one less than that of the numerator. The IMC filter time constants are tuned to provide a balance of robustness and performance for both regulatory and servo problems. We apply the suggested controller to many processes to prove its applicability and effectiveness. Zafer Bingul and Oguzhan Karahn [14] used particle swarm optimization and artificial bee colony algorithms for tuning and designing proportional integral derivative controllers. Chacon et al.[15] have suggested that conventional controllers can be modified to cope with different control requirements. He used different optimization algorithms to determine the best controller parameters. Amirreza Tootchi et al. [16] has developed mathematical expressions for the air levitation system and explored the choice of PID controller for air levitation. In controller design, Mohammed Irshad and Ahmad Ali [17] used a well-known integral performance approach. In this approach, a new objective function is proposed with modifications to the integral of squared error (ISE) criterion for controller design. Using suggested tuning rules, Zhang et.al [18] have designed differential forward proportional integral derivatives for systems with direct synthesis and time delay.

The objective of this research work is to design a PID controller using simplified analytical expressions by applying a multiple dominant pole placement technique. These pole placement methods are used to design the desired characteristic equation. This method assumes the existence of a stable real dominant pole, whose multiplicity increases from one to the number of the adjustable parameters of the designed controller. The proposed PID controller has four adjustable parameters. The major contribution of this work is the deriving tuning rules of efficient PID controllers by using multiple dominant pole placement technique. The proposed method can achieve excellent performance with minimum control effort. The rest part of paper is organized as below. Section 2 delivers mathematical models of PID controllers. Section 3 contains performance indices and time domain specifications. Section 4 gives results of simulation on different processes. Section 5 shows experimental implementation of projected work. Section 6 summarizes the conclusions of the projected work.

Bharat Kumar Shamrao Patil et.al [19] Higher solicitation not withstanding defer time (HOPDT) frames are suggested to use a discrete time sliding mode controller (DSMC). A sliding mode surface is chosen, and the dominating post-circumstance technique is used to resolve the tuning parameters of the sliding mode controller as part of the structural states and botch. The "ball in a barrel" control object regulates the speed of a fan that forces air into a chamber in order to maintain a ball hanging in the barrel at a certain, predetermined location.

Bharat S. Patil et.al [20] PID controllers are commonly utilized in industrial control systems because of their straightforward operating principles. PID controllers are used in daily life by numerous control and instrument engineers and operators. Numerous changes are possible with PID controllers, enabling them to handle a broad range of systems and circumstances. The PID controller's settings must be fine-tuned in order to improve performance. Numerous authors have adjusted PID controller settings using various optimization strategies. The performance of these optimization strategies is lower. This study proposes a refined PID controller for the air levitation system.



II. MATHEMATICAL EQUATIONS

FIGURE 1 shows the block diagram of the proposed system. The controller alters the conditions in the plant according to PID tuning rules.

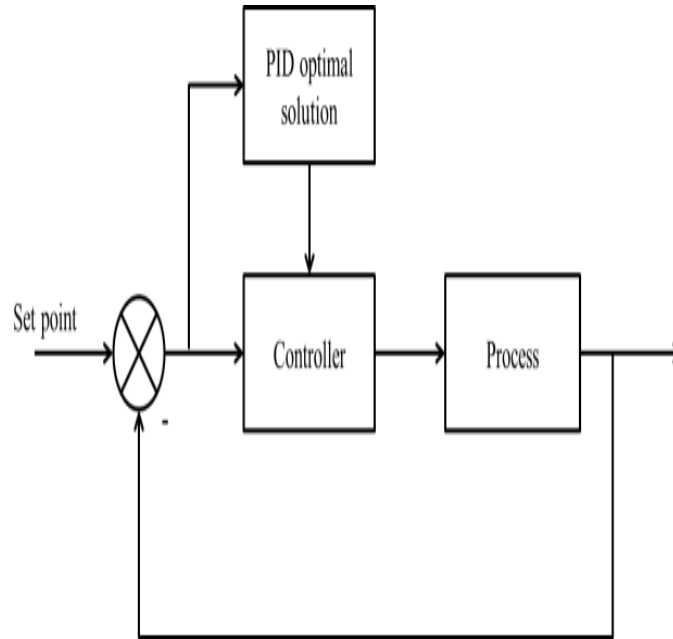


Figure 1: Structure of the closed loop control

The following is a general process transfer function for an integrating system with two additional poles

$$G_p = \frac{k}{s(\zeta_1 s + 1)(\zeta_2 s + 1)} \tag{1}$$

PID controllers can be written as follows

$$G_c = K_c \left(1 + \frac{1}{\zeta_i s} + \zeta_D s \right) \tag{2}$$

An equation describing the characteristics of a system

$$N = 1 + G_p G_c = 0 \tag{3}$$

By substituting equations (1) and (2) into equation (3), the characteristic equation becomes

$$N = 1 + \frac{k}{s(\zeta_1 s + 1)(\zeta_2 s + 1)} \cdot \frac{k_c \zeta_i s + k_c + \zeta_i \zeta_D k_c s^2}{\zeta_i s} = 0 \tag{4}$$

$$\therefore 1 + \frac{k_c k \zeta_1 \zeta_D s^2 + k k_c \zeta_1 s + k k_c}{s(\zeta_1 \zeta_2 s^2 + \zeta_1 s + \zeta_2 s + 1)(\zeta_i s)} = 0$$

$$\therefore 1 + \frac{k_c k \zeta_1 \zeta_D s^2 + k k_c \zeta_1 s + k k_c}{s^4 \zeta_1 \zeta_2 \zeta_i + s^3 \zeta_1 \zeta_1 + s^3 \zeta_2 \zeta_1 + s^2 \zeta_1} = 0$$

$$\therefore \frac{\{\zeta_1 \zeta_2 \zeta_i s^4 + \zeta_i (\zeta_1 + \zeta_2) s^3 + (k_c k \zeta_1 \zeta_D + \zeta_i) s^2 + k_c k \zeta_1 s + k_c\}}{s(\zeta_1 \zeta_2 s^2 + \zeta_1 s + \zeta_2 s + 1)(\zeta_i s)} = 0$$

$$\therefore \frac{\{\zeta_1 \zeta_2 \zeta_i s^4 + \zeta_i (\zeta_1 + \zeta_2) s^3 + (k_c k \zeta_1 \zeta_D + \zeta_i) s^2 + k_c k \zeta_1 s + k_c\}}{s^4 \zeta_1 \zeta_2 \zeta_i + \zeta_i (\zeta_1 + \zeta_2) s^3 + \zeta_1 s^2} = 0$$

$$\therefore \zeta_1 \zeta_2 \zeta_i s^4 + \zeta_i (\zeta_1 + \zeta_2) s^3 + (k_c k \zeta_1 \zeta_D + \zeta_i) s^2 + k_c k \zeta_1 s + k_c = 0 \tag{5}$$

The desired characteristic equation of the system is as follows:

$$(\lambda s + 1)^4 = 0 \tag{6}$$

$$\therefore (\lambda s + 1)^4 = \lambda^4 s^4 + 4\lambda^3 s^3 + 6\lambda^2 s^2 + 4\lambda s + 1 = 0 \tag{7}$$

By comparing equation (5) with equation (7), the following equations get obtained

$$\lambda^4 - \zeta_1 \zeta_2 \zeta_i = 0 \tag{8}$$

$$4\lambda^3 - \zeta_i (\zeta_1 + \zeta_2) = 0 \tag{9}$$

$$6\lambda^2 - (k_c k \zeta_1 \zeta_D + \zeta_i) = 0$$

$$\lambda^2 - \frac{k_c k \zeta_1 \zeta_D}{6} - \frac{\zeta_i}{6} = 0 \tag{10}$$



$$4\lambda - k \cdot k_c \zeta_i = 0 \tag{11}$$

$$1 - k \cdot k_c = 0 \tag{12}$$

Tuning parameter λ is directly related to controller parameters. Advance Genetic Algorithms can solve simultaneous equations (8) - (12) by selecting diverse value of λ for better performance.

III. PERFORMANCE INDICES AND TIME DOMAIN SPECIFICATIONS

3.1 performance index value

By changing the operating control system, modern control schemes maintain system parameters at an optimal level of performance under varying inputs. Generally, control systems are designed to meet particular performance requirements. Performance specifications are determined by a standard step input signal and a measured signal generated by the system. In this study, we considered two performance indices i) integral square error (ISE), ii) integral absolute error (IAE). For a given system, the error is defined as the difference between the set point and the measured value. It is calculated according to the following equation:

$$E(t) = r(t) - c(t) \tag{13}$$

Where, the error signal at time t is $e(t)$, $r(t)$ is the reference input signal, and $c(t)$ is the output signal. In the above performance index values, time reaches infinity and the error reaches zero.

i) The Integral Square Error Criteria (ISE)

As a result of the Integral Square Error (ISE) criterion, the quantity of system performance is evaluated by the following integral.

$$ISE = \int_0^{\infty} e^2 dt \tag{14}$$

A system with the minimum integral can be designed as an optimal system. Since this integral can easily be computed, these criteria can be applied to both deterministic and static inputs.

ii) Integral Absolute Error (IAE)

Integral Absolute Error (IAE) is a criterion for evaluating system performance.

$$IAE = \int_0^{\infty} |e| dt \tag{15}$$

This is a simple performance criterion based on computation. It normally produces reasonable damping and satisfactory time response.

3.2 Time Domain Specifications

A control system's performance characteristics are usually described in terms of time domain specifications. The output response of an excellent closed loop system should be:

i) Minimum rise time (T_r).

ii) Fixed settling time (T_s).

iii) No steady state error (e_{ss}).

Following is a description of how the following time domain specifications are obtained.

3.2.1. Rise Time (T_r): It is the time it takes for the response to rise from 10% to 90% of the final value for over damped systems and from 0 to 100% for under damped systems. The rise time is reciprocal to the slope of the response at the instant the response equals 50% of the final value.

$$t_r = \frac{\pi - \theta}{\omega_n \sqrt{1 - \xi^2}} \text{ Sec} \tag{16}$$

3.2.2. Peak Time (T_p): The response takes time to reach its peak value. It is also defined as the time at which the response undergoes the first overshoot, which is always peak overshoot.

$$t_p = \frac{\pi}{\omega_n \sqrt{1 - \xi^2}} \text{ Sec} \tag{17}$$

3.2.3. Settling Time (T_s):

It is the amount of time it takes for the response to decrease and remain within a specified percentage of final value (within the tolerance band).

$$T_s = \frac{4}{\xi \omega_n} \text{ Sec} \quad (18)$$

IV. PROPOSED EXPERIMENTAL SETUP

The experimental setup consists of a clear plexiglass tube 1m elongated with a 40mm diameter. The airflow in the tube is controlled by a DC fan fitted to the end of the bottom of the pressure box, given in Figure 2.

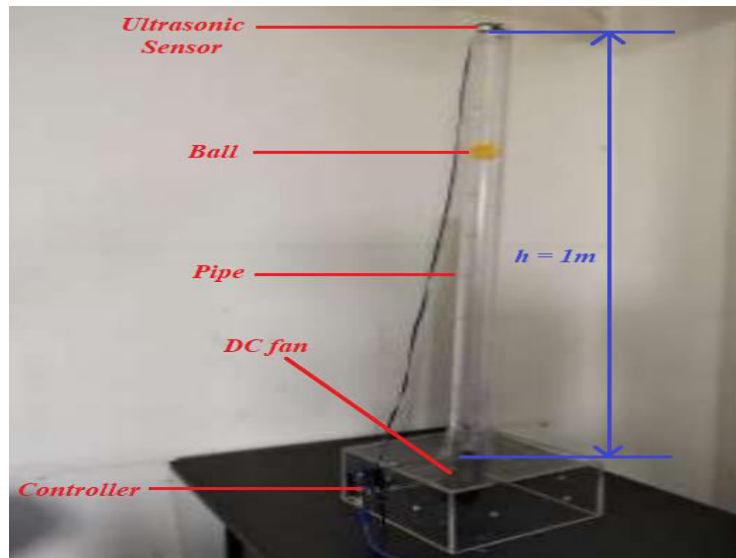


Figure 2. Hardware of proposed system

Ultrasonic SRF04 sensor is mounted on the tube so that they can number the ball's position. It provides an echo pulse proportional to the distance. The pulse generator sends out a signal with amplitude 1, frequency 0.05 and duty cycle 0.02 to the trigger input from the timing drawing of the ultrasonic sensor. The time of traveling of the sound wave is the change between the magnitude edges of the trigger input signal and the line of echo of the ultrasonic sensor. The fan is to provide the air needed to lift the ball inside the tube. The airflow supplied for lifting a ball is relative to the applied voltage to the fan, which is relative to PWM duty cycle. This duty cycle value is depending on the PID design that we will use for the ball-in-tube experiment. Proposed system for Air Levitation has shown in Figure5. Hardware controller circuit is intended to control the experimental setup. Circuit uses an ATMEGA328 microcontroller. The ultrasonic sensor is straight linked to the controller as both are running on Transistor-Transistor Logic (TTL). MOSFET IRF540 is utilized to control the DC fan. The gate pulses from the microcontroller in the form of PWM control the speed of the DC fan. The time measured by the controller from the ultrasonic sensor is consistent to the height of the ball in the tube. The 29.412 μ s to 2941.2 μ s sound wave time from the ball to the sensor is converted from the distance 1 cm to 100cm. Height of the ball is fed as the PID based controller input which algorithm is written in microcontroller. The remedial action is then taken in the form of PWM as an output. This signal from PWM is then provided as a gate input to the MOSFET which results in corresponding speed action of the DC fan. Ultrasonic sensor transmits the sound wave at the same time the timer gets started. That sound wave smashes the ball and then reflects the wave back. Once this wave is received by the sensor the timer stops. This sound wave's traveling time is noted and converted to the distance. This value is then passed to the controller which returns a signal from the PWM for controlling the speed of the DC fan. This cycle repeats in a forever loop with resolution of 20 readings per second.

V. SIMULATION STUDIES AND RESULTS

For demonstration the usefulness of the suggested method, a few case studies were examined. Performance of the proposed technique was associated with recent methods stated in the literature. The performance results of case studies proposed by Sigurd [3], Jin and Ziu [10], Ajmeri and Ali [11], Zafer Bingul and Oguzhan Karahn [14] and J Chacon et



al. [15]. The performances of proposed methods for PID controller designing and the existing some methods have given in Table 1 to Table 6. Different case studies have discussed in details as below. Three examples are given below to illustrate the usefulness of the proposed method. The results are compared to those from PID parameters suggested by some authors for controlling integrating processes.

5.1 Example 1

Consider integrating first order plus time delay plant (IFOPTD)

$$P(s) = \frac{0.5}{s(s+1)} e^{-15s} \tag{19}$$

In According to Zafer Bingul and Oguzhan Karahn [14], Zafer used optimization algorithms to determine the optimal PID for IFOPTD. The PID controller parameters calculated by Bingul-PSO are $K_p = 0.0951$, $K_i = 0.000001$, $K_d = 0.0795$ and PID parameters calculated by Bingul-ABC are $K_p = 0.1098$, $K_i = 0.000001$, $K_d = 0.0709$.

As a result of rearrangement, the above equation(19) becomes.

$$P(s) = \frac{0.033}{s(s+1)(0.067s+1)} \tag{20}$$

From equations (8) to (12), proposed method provides values for PID parameters such as $K_p = 1.4$, $K_i = 0.0001$, $K_d = 0.041$. The step response for this process is shown in figure 2a. and figure 2b. for servo as well as regulatory applications. ISE, IAE, serror, TV, time response specifications (rise time, settling time, peak time) are shown in Table 1 and Table 2 for servo and regulatory applications respectively. The experimental results indicate that the proposed method has excellent performance.

Table1a. Time response specifications and performance indices for example-1.
(For servo response)

Parameters of PID and Filter / Performance Measures	Proposed	Bingul (PSO) Ref.[14]	Bingul (ABC) Ref.[14]
K_p	1.4	0.0951	0.1098
K_i	0.0001	0.000001	0.000001
K_d	0.041	0.0795	0.709
Rise time in second	44.5436	686.7795	595
Settling time in second	79.3387	1.1902e+03	1.0391e+03
Overshoot	0.0822	0.2223	0.1413
Peak time	1.0008	2.172e+03	1.8766e+03
serror	0.0017	0.002	0.0028
ISE	4.942	5.895	5.885
IAE	5.43	5.947	5.942
Tv	0.0620	0.0664	0.0665



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Table1b. Time response specifications and performance indices for example-1.
(For regulatory response)

Parameters of PID and Filter / Performance Measures	Proposed	Bingul (PSO) Ref.[14]	Bingul (ABC) Ref.[14]
Kp	1.4	0.0951	0.1098
Ki	0.0001	0.000001	0.000001
Kd	0.041	0.0795	0.709
Settling time in second	5.4839e+04	3.7292e+05	4.3038e+05
Settling time in second	79.3387	1.1902e+03	0.9021
Peak time in second	0.7086	1.8061e+03	1.6373e+03
sserror	0.9973	0.9938	0.9703
ISE	1	87.4397	63.9096
IAE	5.43	5.947	5.942
Tv	0.0206	4.6299	3.4453

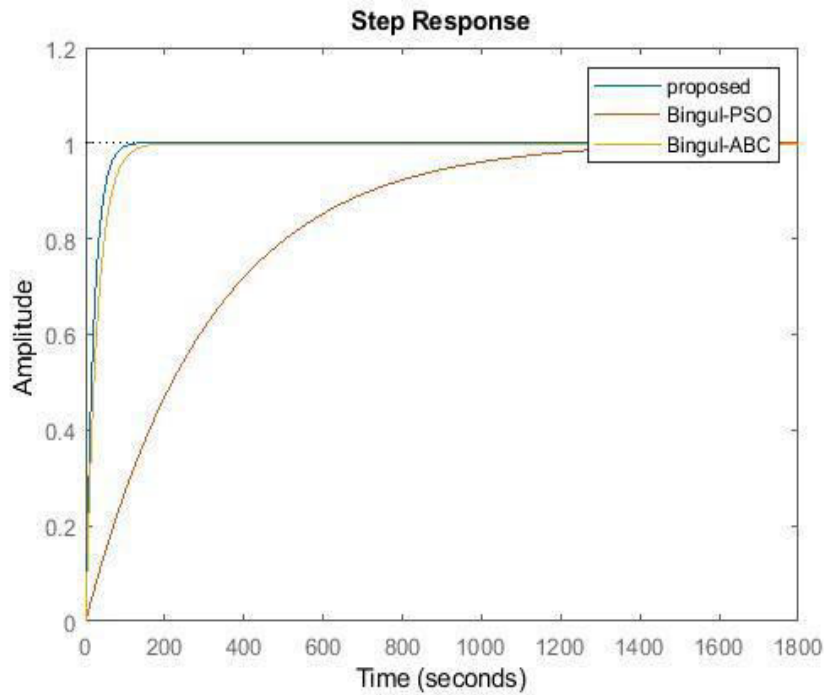


Figure 2a: Step servo response for example 1.

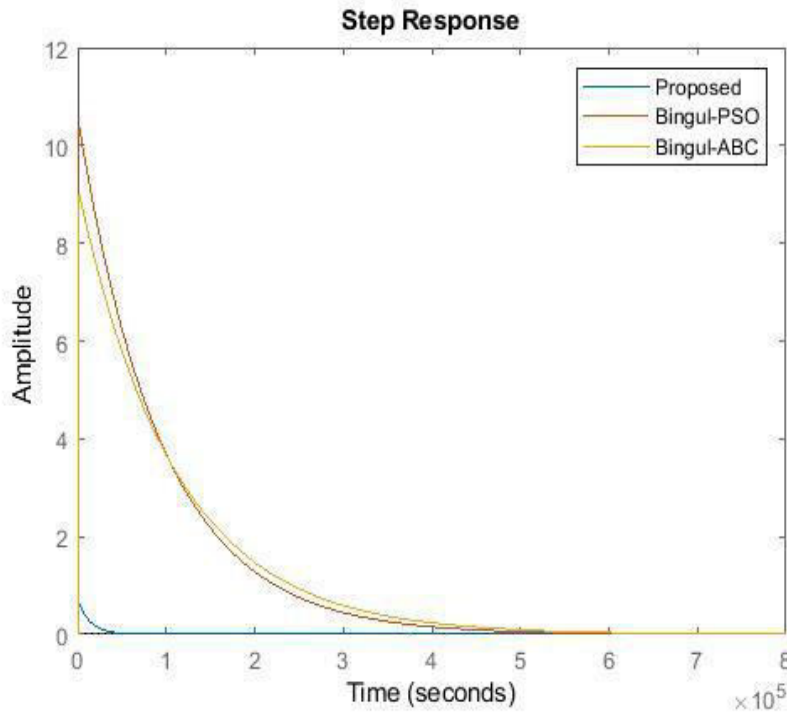


Figure 2b. Step regulatory response for example 1.

5.2 Example 2.

Take a look at a plant

$$P(s) = \frac{0.2e^{-s}}{s(4s+1)}$$

As a result of rearrangement of above equation, it becomes.

$$P(s) = \frac{0.2}{s(4s+1)(s+1)} \tag{21}$$

From equations (8) to (12), proposed method provides values for PID parameters such as $K_p = 3.301$, $K_i = 0.0111$, $K_d = 9.12$. The PID parameters calculated by Jin and Ziu [10], for this process are $K_p = 3.686$, $K_i = 0.3547$, $K_d = 9.1155$. As per Ajmeri and Ali [11] values of parameters of PID are $K_p = 3.67$, $K_i = 0.3521$, $K_d = 9.09$. Closed loop response is shown in figure 3a. and figure 3b for servo and regulatory applications, indicating that the proposed method gives a faster response than existing methods. Table 2a and table 2b shows performance indices and time response specifications in terms of servo and regulatory applications, demonstrating how well the proposed method performs.

Table.2a. Time response specifications and performance indices for Example-2.
(For servo response)

Parameters of PID and Filter / Performance Measures	Proposed PID Controller	Ch.Anil Ref.[12]	Jin and Liu Ref.[10]	Ajmeri and Ali Ref.[11]
Kp	3.301	5.7422	3.686	3.67
Ki	0.0111	0.9725	0.3547	0.3521
Kd	9.12	11.21	9.1155	9.09



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α	-	0.6320	-	-
β	-	0.4915	-	-
Rise time in second	2.7477	1.9228	2.4915	2.4985
Settling time in second	10.8514	16.8464	15.3136	15.4001
Rise time in second	2.7477	0.364	2.4915	2.4985
Settling time in second	10.8514	16.8464	15.3136	15.4001
Peak time	6.2272	5.2730	1.3111	6.5375
sserror	0.0017	0.0114	0.0016	0.0015
IAE	2.269	4.408	2.447	2.449
ISE	1.527	1.579	1.572	1.573
Tv	0.083	0.0587	0.0610	0.0609

Table.2b. Time response specifications and performance indices for Example-2.
(For regulatory response)

Parameters of PID and Filter / Performance Measures	Proposed PID Controller	Ch.Anil Ref.[12]	Jin and Liu Ref.[10]	Ajmeri and Ali Ref.[11]
Kp	3.301	5.7422	3.686	3.67
Ki	0.0111	0.9725	0.3547	0.3521
Kd	9.12	11.21	9.1155	9.09
α	-	0.6320	-	-
β	-	0.4915	-	-
Settling time in second	10.8514	16.8464	15.3136	15.4001
sserror	0.9985	1.006	1.00	1.00
IAE	1.001	1.5300	1.420	1.334
Tv	0.0110	0.0045	0.0063	0.0064



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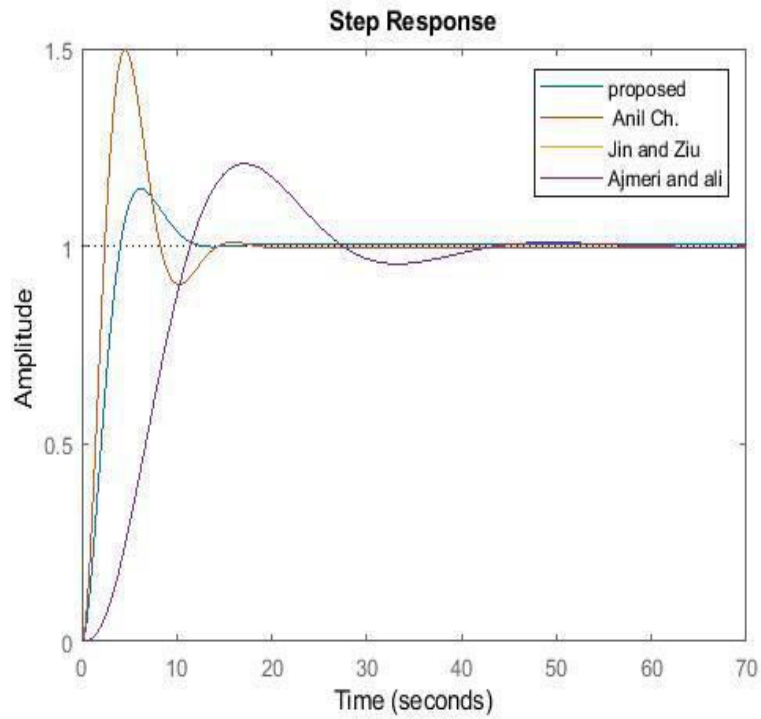


Figure 3a: Step response for example 2.

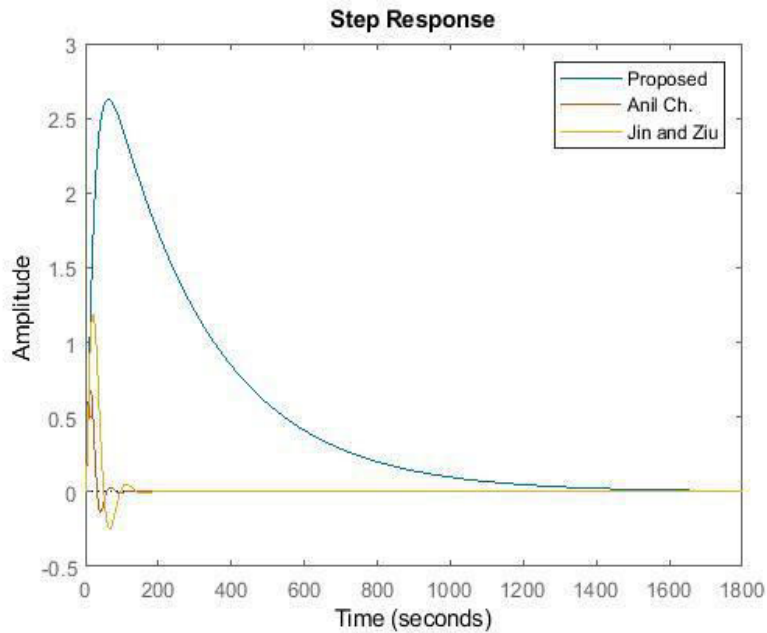


Figure3b: Step regulatory response for example2.



5.3 Example 3.

Mathematical equation of air levitation system is,

$$H_p(s) = \frac{0.88}{s(3.023s+1)(s+1)} \tag{22}$$

From equations (8) to (12), proposed method provides values for PID parameters such as $K_p = 1.3332$, $K_i = 0.2825$, $K_d = 1.903$. The proportional-integral-derivative controller’s parameters by J. Chacon et al. [15] and Sigurd [3] method are shown in table 3a and table 3b for servo as well as regulatory applications and .A closed loop response is shown in figure 4a and figure 4b for servo as well as regulatory applications, indicating that the proposed method gives a faster response than existing methods. Table 3a table 3b also shows performance indices and time response specifications for servo as well as regulatory applications, demonstrating how well the proposed method performs.

Table.3a. Time response specifications and performance indices for Example-3.
(For servo response)

Parameters of PID and Filter / Performance Measures	Proposed	Chacon Ref.[15]	Sigurd Ref.[3]
K_p	1.3333	0.005	0.05624
K_i	0.2825	0.002	0.007
K_d	1.903	0	0.17
α	100	100	100
β	0.01	0.01	0.01
Rise time in Second	0.0052	1.1625	0.0312
Settling time in Second	0.0718	9.4264	0.1480
sserror	0.0030	0.00680	0.0211
Peak time in Second	0.0137	2.7882	0.0620
ISE	1.997	5.328	1.503
IAE	1.002	5.642	2.266
T_v	0.0471	0.0625	0.1098



Table.3b. Time response specifications and performance indices for Example-3.
(For regulatory response)

Parameters of PID and Filter / Performance Measures	Proposed	Chacon Ref.[15]	Sigurd Ref.[3]
Kp	1.3333	0.005	0.05624
Ki	0.2825	0.002	0.007
Kd	1.903	0	0.17
α	100	100	100
β	0.01	0.01	0.01
sserror	0.8521	1.1625	1.1232
ISE	3.997	5.328	2.503
IAE	3.002	5.642	4.266
Tv	0.0081214	0.8833	0.0559

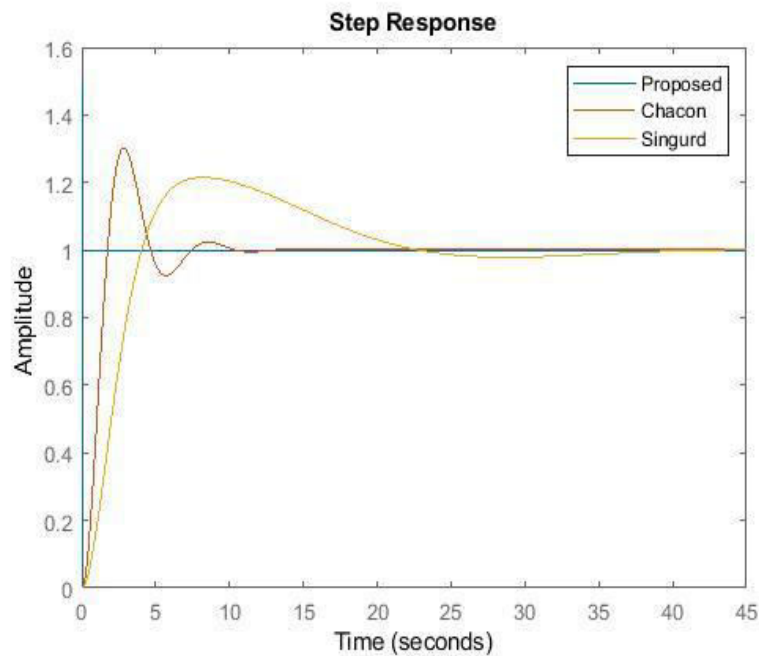


Figure 4a. Step Servo response for example 3.

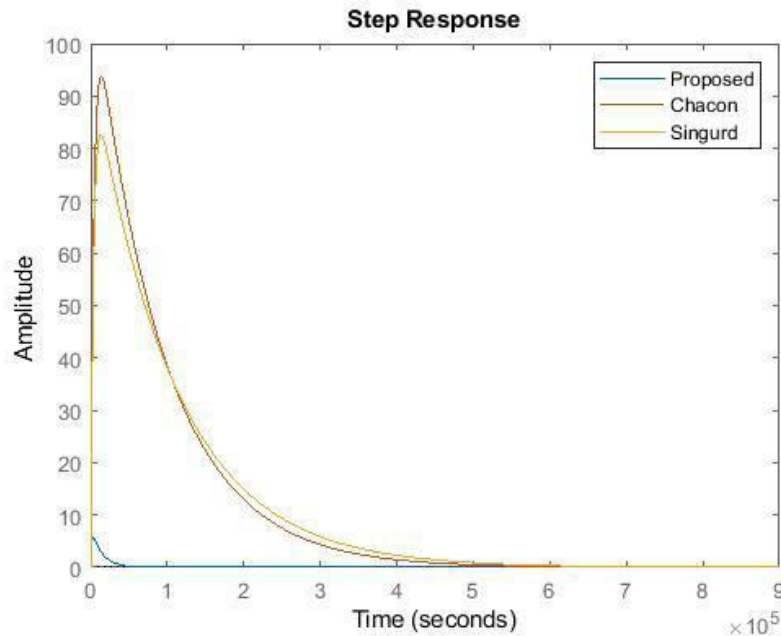


Figure 4b Step regulatory response for example3

VI. CONCLUSIONS

Using multiple dominant pole placement technique, a PID controller for integrating first order plus time delay processes is developed. Analytical formulas are given to calculate the PID parameters. Simple tuning rules are given to achieve the desired performance. Four adjustable parameters are used to design the controller. Simulation results show the proposed method has better performance in terms of ISE, IAE, serror, T_v , settling time, rise time, peak time than existing developed methods. The proposed method is compared with recently presented methods. The designed controller is found to be both effective in terms of performance and input usage when compared to other methods.

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