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Performance analysis of IMC-PID controller on PCT-14 air pressure control system ☆,☆☆

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A R T I C L E I N F O

Method name:
IMC-PID

Keywords:
IMC
PID
Controller
Performance analysis
Pressure control system

A B S T R A C T

This research presents a comprehensive performance analysis of the IMC-PID controller implemented in the PCT-14 air pressure control system, a platform ideal for experimenting with various control methodologies. The study aims to compare the effectiveness of the IMC-PID controller with IMC-PIDF, Good Gain - PID and Skogestad's - PI controllers, focusing on response time characteristics based on the simulation of the PCT-14′s transfer function. Performance analysis is conducted by comparing system response characteristics to set point changes, including rise time, overshoot, settling time, peak time, and steady-state error. To validate the controller's effectiveness, performance index value such as Integrated Absolute Error (IAE) was calculated. The research findings indicate that the IMC-based PID controller outperforms the Good Gain – PID, Skogestad-PI, and IMC-PIDF controllers in handling set point changes.

- Simulating the transfer function of the PCT-14 air pressure control system to examine the response time characteristics of the IMC-PID, IMC-PIDF, Good Gain - PID, and Skogestad's - PI controllers.
- Conducting a performance analysis by comparing system response characteristics in response to changes in set point values.
- Calculating performance index value, IAE to assess the controllers' effectiveness.

Specification table

Subject area:	Mathematics
More specific subject area:	Applied Mathematics – Control Theory
Name of your method:	IMC-PID
Name and reference of original method:	None
Resource availability:	None

☆ **Related research article:** None
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Background

One of the control systems commonly used in the industrial world is the air pressure control system. Air pressure controllers in industry are systems or devices designed to regulate and monitor air pressure levels in an industrial environment. The aim is to ensure that the air pressure is regulated according to the specific requirements of a particular industrial process.

The air pressure control module, the Pressure Control Trainer (PCT)−14 in the Process Control Laboratory of the Chemical Engineering Department at Politeknik Negeri Malang is a pressure control practicum tool that provides students a realistic understanding of how the control system functions. This module is equipped with a Programmable Logic Controller (PLC) and a Human Machine Interface (HMI), which works online and in real time when reading data from the controlled system [1]. The PCT-14 is designed for educational purposes, providing a practical platform for students to learn about process control techniques and control theory.

In the PCT-14 pressure control module, the PID controller is the primary controller in use. The values of PID control parameters can influence the response characteristics of the system. Tuning PID parameter values can be done using several methods. The method that have been used for tuning PID parameters on the PCT-14 pressure control module are the Skogestad method [2]. Meanwhile, the methods that have been used to simulate the transfer function of the PCT-14 air pressure control system are Good Gain, Cohen-Coon, and Ziegler-Nichols [1]. The results of several PID tuning methods are simulated on the PCT-14 air pressure control system through the block diagram. The results of research conducted [1] show that all PID controller parameters used produce small errors when the setpoint was changed by 20 % from the initial position. Of the several methods used, the Skogestad method shows the best tuning results for the PI controller and the Good Gain method for the PID controller. The response performance, in terms of a settling time, is 14 s for the PID controller and 13 s for the PI controller, with a slight offset of 1 %. The PCT-14 is often used in laboratory settings to demonstrate how different control strategies.

Other methods that can be used to tune PID controller parameter values include trial and error as done by [3–7]; auto-tuning as done by [6,8] and [9]; genetic algorithm as done by [5,6,10–12]; and Tyreus-luyben as done by [12–16]. Apart from that, another method for tuning PID parameter values is Internal Model Control (IMC). Simulation results in research [17] show that the IMC-PID controller has better dynamic performance in set-point tracking, disturbance rejection, and resistance to changes in system parameters and the outlet pressure can be controlled well. IMC-PID with varying λ values was also used by [18] in the design of the Shell and Tube Heat Exchanger Segmental Baffle temperature control system. The results obtained showed that IMC-PID with lambda ($\lambda > 0.1\tau$) provided good results, particularly in maintaining stability even when disturbances were added, as the resulting IAE value was small. Therefore, this method shows the best results among various control methods used. The IMC-PID controller design method was also successfully tested on a nonlinear bioreactor process model [19]. The suggested controller effectively managed the bioreactor's temperature in both setpoint and disturbance change scenarios. IAE, ISE, and ITAE were used to assess the controller's performance, with corresponding values of 20.99, 49.02, and 292.50, respectively. The suggested approach outperforms previously documented strategies for bioreactor temperature management in terms of IAE and settling time during closed-loop operations. Performance analysis of comparison and speed control of DC Motor and DC Servomotor in [20] showed that IMC-PID controller gave the best performance than Ziegler-Nichols, PI, and PID Controller. This brief literature review showed that IMC-PID controller design is a well-explored topic because it yields good results and good performance in its response.

This research aims to build upon the work of [1] by using the Internal Model Control (IMC) method to tune the PID parameter values of the PCT-14 air pressure control module via a system block diagram. By using the PCT-14 transfer function, the tuning results are simulated to provide an overview of the system response characteristics. Subsequently, a performance analysis is conducted using the IMC-PID controller, focusing on metrics such as rise time, peak time, overshoot, and settling time. To validate the effectiveness of the controller, performance index value such as integrated Absolute Error (IAE) was also calculated.

Method details

The stages of this research began with a literature study on the PCT-14 air pressure control module and the IMC-PID controller. This was followed by designing the block diagram of the PCT-14 air pressure control system. Next, the PID parameters were tuned using IMC method. The filter parameter value λ was then determined using the trial and error method. Subsequently, the results of the IMC-PID tuning were simulated on the pressure control system using MATLAB/SIMULINK online version. The simulation aims to observe the system's response to a 20 % change in the setpoint value. An analysis of the control system's performance is then carried out by evaluating the characteristics of the system's transient response (overshoot, settling time, rise time, steady-state error). Additionally, the efficiency and performance of the controller are evaluated using the IAE. Finally, the performance of the IMC-PID controller is compared with other methods, such as Good-Gain, Cohen-Coon, and Skogestad, to determine which method performs better in managing setpoint changes in the PCT-14 air pressure control system. Finally, the performance was analyzed, and conclusions were draw.

PCT-14 air pressure control module

The PCT-14 is a specialized educational tool commonly used to teach and demonstrate process control principles in academic or training environments. The PCT-14 makes an excellent platform for learning and experimenting with different control methodologies. The schematic of the PCT-14 air pressure control module is presented in Fig. 1. The compressor provides compressed air, which is the main raw material used in this control module. Two streams are created from the compressed air: one flows upward to actuate the control valve, and the other goes down the process pipe. The compressed air flowing through the process pipe passes through V2 and

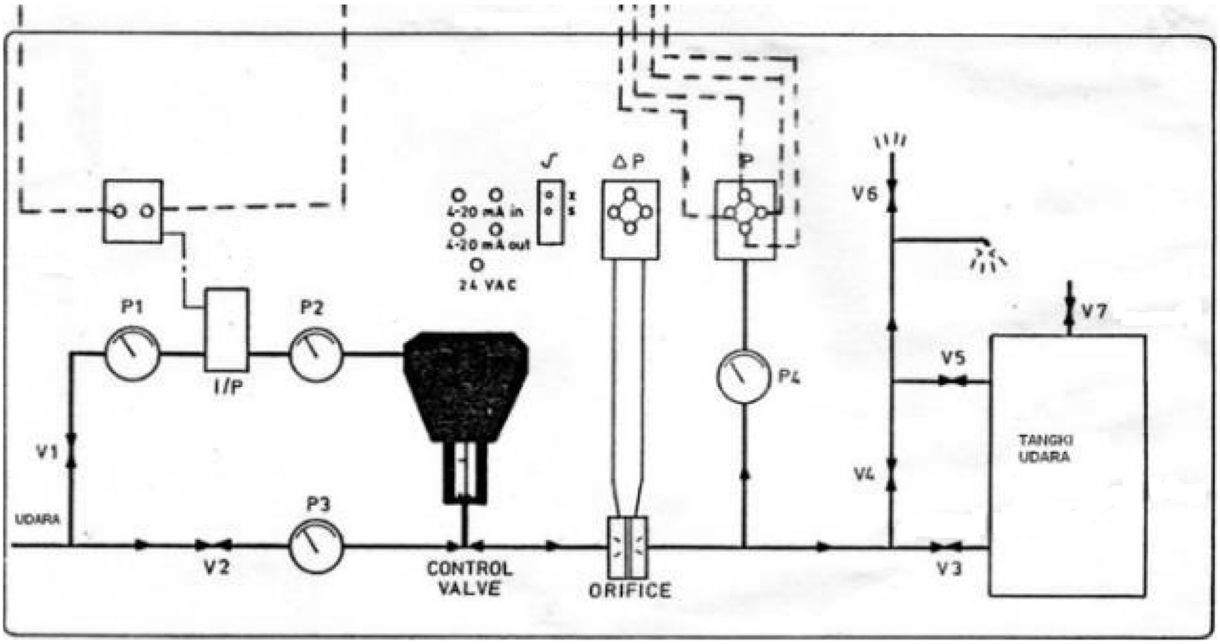

Fig. 1. Equipment schematic of PCT 14 air pressure control module [1].

is measured at P2, while the compressed air driving the control valve passes through V1 and is measured at P1. The compressed air, functioning as a process fluid, is measured at the orifice and read at P4. The Pressure Control Module armfield PCT-14 is presented in Fig. 2. [1]. where:

V1, V2: *Pressure regulator valve*

V3, V4, V5, V6: *Selector valve*

V7: *Relief valve*

P1, P2, P3, P4: *Pressure gauge Indicator*

And then, the block diagram of the air pressure control system transfer function is presented in Fig. 3.

The transfer function of the block diagram [1] is

$$\text{Control valve} = \frac{0,035}{s+1} \tag{1}$$

$$\text{Process} = \frac{1,203}{7,83s+1} \tag{2}$$

$$\text{Sensor} = \frac{1}{0,04s+1} \tag{3}$$

IMC structure

IMC or internal model control is a type of control strategy for controller design based on mathematical process models introduced by Garcia and Morari (1982). IMC develops tuning rules for feedback controllers [22,23]. IMC is based on exact models derived from mathematical models of processes. The control system produces reliable and stable results. A control system that maintains appropriate control actions for dynamic changes in the control system is said to be stable. The IMC controller proficiently manages time delays and enhances control performance, resulting in quicker response times and improved accuracy. Incorporating an internal model that accurately represents the system's dynamics allows IMC to effectively address unstable poles and zeros during the design process [24–29]. The structure of the IMC is presented in Fig. 4.

IMC consists of a controller, an object model, and a filter. The object model is used to predict the influence of variables on system output. The controller then calculates the future output value and ensures the system output tracks the given value. The filter, which is inserted into the controller, enables the controller to be physically realized, and improve the system's stability by ensuring control quality. In Fig. 4, G_c represents the controller, G_p represents the process/plant, $\tilde{G}$ represents the internal model. Y_s is the set-point, Y is the output, and D is disturbance from outside the system. The mathematical model depicted in Fig. 4 is shown in Eqs. (1)–(3).

$$E(s) = Y_s(s) - \left(Y(s) - \tilde{Y}(s)\right) \tag{4}$$

$$U(s) = E(s)G_c(s) \tag{5}$$

Fig. 2. Armfield PCT-14 pressure control module [21].

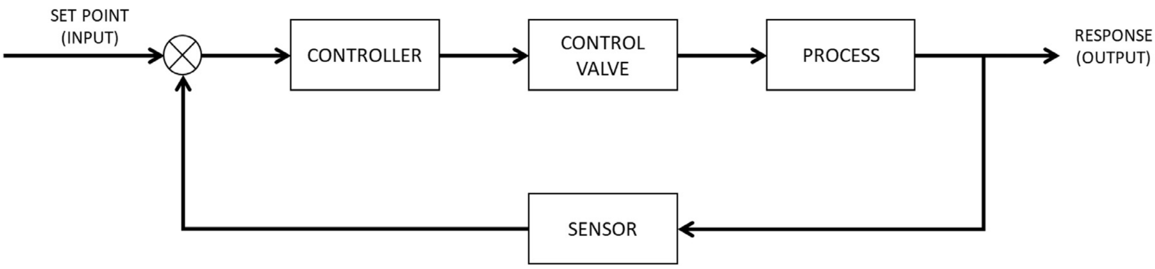

Fig. 3. The block diagram of the PCT-14 air pressure control system.

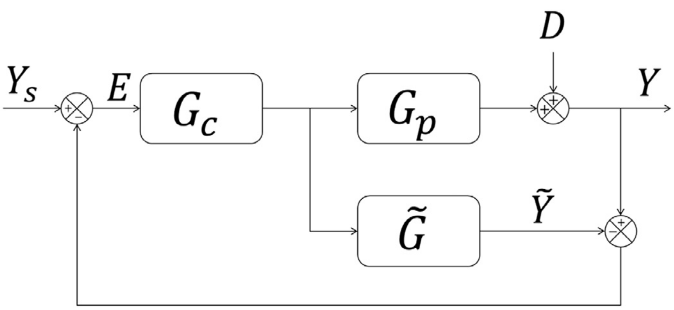

Fig. 4. IMC structure.

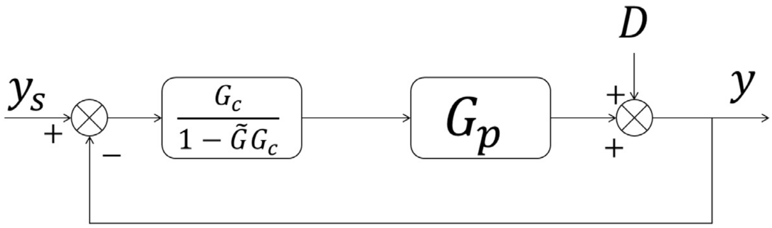

Fig. 5. Standard feedback diagram.

$$Y(s) = U(s)G_p(s) + D(s) \tag{6}$$

$$\tilde{Y}(s) = U(s)\tilde{G}(s) \tag{7}$$

Substitute Eqs. (4), (6), and (7) into Eq. (5), so that

$$U(s) = \frac{\left(Y_s(s) - D(s)\right)G_c(s)}{1 + \left(G_p(s) - \tilde{G}(s)\right)G_c(s)} \tag{8}$$

Substitute Eq. (8) into Eq. (6), so that

$$Y(s) = \frac{Y_s(s)G_c(s)G_p(s) + \left(1 - \tilde{G}(s)G_c(s)\right)D(s)}{1 + \left(G_p(s) - \tilde{G}(s)\right)G_c(s)} \tag{9}$$

If $\tilde{G}(s) = G_p(s)$ and $G_c(s) = \tilde{G}^{-1}(s)$ then based on Eq. (9) we obtain $Y(s) = Y_s(s)$ indicating that control was successfully executed, achieving an optimal response to changes in the set point.

IMC design

The following are the stages in designing IMC:
1. Determine the transfer function of the Internal model $\tilde{G}(s)$ that represents the process
2. Factorize the internal model $\tilde{G}(s)$ into invertible and non-invertible components:

$$\tilde{G}(s) = \tilde{G}_+(s)\tilde{G}_-(s) \tag{10}$$

Here, $\tilde{G}_+(s)$ is the invertible component and $\tilde{G}_-(s)$ is the non-invertible component. And $\tilde{G}_-(s)$ includes all time delays and right-half plane (RHP) zeros, ensuring that $\tilde{G}_+(s)$ is stable and free of predictors. The non-invertible component $\tilde{G}_-(s)$ has characteristics that, if inverted, would render the system unstable [30].

3. Design the IMC controller $G_c(s)$

$$G_c(s) = \left(\tilde{G}_+(s)\right)^{-1} f(s) = \left(\tilde{G}_+(s)\right)^{-1} . \frac{1}{(\lambda s + 1)^n} \tag{11}$$

where $f(s) = \frac{1}{(\lambda s+1)^n}$ represents the low-pass filter. Here, λ denotes the IMC controller filter parameter (filter time constant), and n is an integer constant that ensures the IMC controller $G_c(s)$ is either proper or semiproper. The controller $G_c(s)$ is considered proper if $n = 1$. [22,30].

Determining the appropriate value for λ typically involves a trial-and-error approach. The robustness, disturbance rejection, and dynamic performance of the system are directly influenced by λ. A larger λ tends to degrade dynamic characteristics while enhancing resistance [31]. Conversly, a smaller λ improves dynamic performance but reduces robustness. Therefore, selecting an optimal λ is crucial for the IMC-PID controller, as it directly affects the desired performance through adjustments to the filter time constant λ. [32]

IMC-PID design

The following are the stages in designing IMC-PID:
1. Determine the IMC controller $G_c(s)$
2. Determine the standard feedback controller which is equivalent to the IMC

The IMC structure is as shown in Fig. 4. can be converted into a standard feedback controller, as shown in Fig. 5.

Let Eq. (12)

$$G_{c1}(s) = \frac{G_c}{1 - \tilde{G}G_c};\ for\ \tilde{G}G_c \neq 1 \tag{12}$$

represents standard feedback controller.

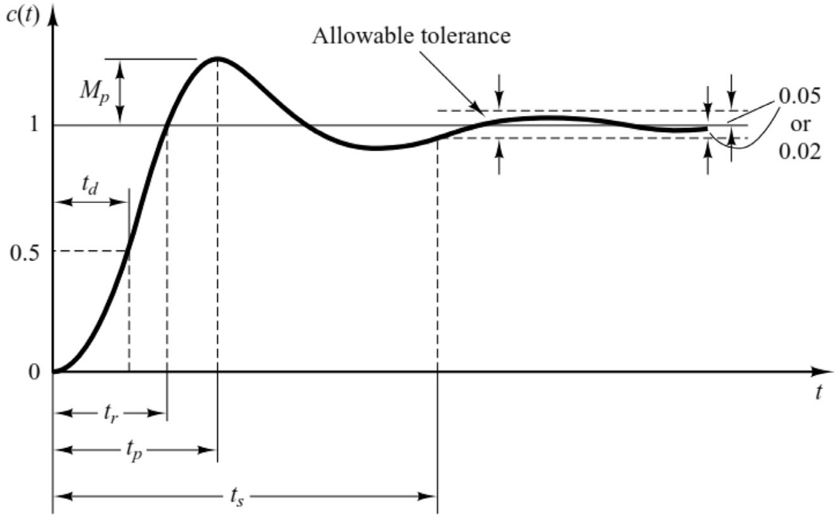

Fig. 6. Transient response graph and specifications [33].

3. Determine the IMC-PID parameters.
The transfer function of PID is shown in Eq. (13) [33].

$$G_{PID} = K_p\left(\frac{T_i T_D s^2 + T_i s + 1}{T_i s}\right) \tag{13}$$

4. Perform closed-loop simulations for the perfect model case and the case with model mismatch. Select the desired λ value as a trade-off between performance and robustness.

Transient response specification

In analyzing control results, the transient response specifications that can be evaluated are [33]:

1. Rise time, t_r is the time required for the response to rise from 10 % to 90 %, 5 % to 95 %, or 0 % to 100 % of the final value. For underdamped second-order systems, a rise time from 0 % to 100 % is usually used. For overdamped systems, a rise time of 10 %–90 % is usually used.

2. Peak time, t_p is the time required for the response to reach the first peak of overshoot

3. Maximum overshoot, M_p: the maximum value of the response curve peak calculated from a value of one. If the steady state response value is less than one then the maximum overshoot value in percent is generally used

$$M_p = \frac{c(t_p) - c(\infty)}{c(\infty)} \times 100\% \tag{14}$$

Where $c(t_p)$ is the peak value and c(∞) is the set point value. In the industrial world, overshoot cannot exceed 8 % –10 % [30].

4. Settling time, t_s is the time required for the response curve to reach and remain within the final value range of the measure determined by the absolute percentage of the final value (usually 2 % or 5 %).

5. The steady state error value is the difference between the reference value (set point) and the output value in a steady/stable state.

The response specifications are shown in Fig. 6.

In addition, the performance of the proposed method is evaluated using the error index IAE (Integral of Absolute Error). IAE is the absolute error integrated over time, providing a measure of the total error without regard to it's direction of the error (positive or negative). Therefore, IAE provides an idea of the extent to which the system response is close to the desired response. So the smaller the Integral of Absolute Error (IAE) value, the better the response results to the setpoint [18]. To get the IAE value, the following equation is used

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

Method validation

In order to obtain response system of the PCT-14 air pressure control system, these were the stage that we have done.

IMC design in PCT-14 air pressure control module

1. Determine the transfer function of the Internal model $\tilde{G}$ (s), which represents the process.
The process transfer function in the PCT-14 air pressure control module is shown in Eq. (16) [1].

$$G_p = \left(\frac{0,035}{s+1}\right)\left(\frac{1.203}{7.83s+1}\right) \tag{16}$$

Because the transfer function of the process is a second order process without time delay, the transfer function of the internal model can be determined to ensure optimal control, as shown in Eq. (17).

$$\tilde{G}(s) = G_p = \frac{0,035}{s+1}\,\frac{1,203}{7,83s+1} = \frac{0,042105}{7,83s^2+8,83s+1} \tag{17}$$

2. Factorize the internal model $\tilde{G}(s)$ into invertible components $\tilde{G}_+(s)$ and non-invertible $\tilde{G}_-(s)$ as shown in Eq. (10). From Eq. (17), we obtained $\tilde{G}_+(s)$ as shown in Eq. (18)

$$\tilde{G}_+(s) = \frac{0,042105}{7,83s^2+8,83s+1} \tag{18}$$

3. IMC controller $G_c(s)$ design
Substitute Eq. (17) into Eq. (12) and choose $n = 1$ for a simple approach, we obtained Eq. (19)

$$G_c(s) = \left(\tilde{G}_+(s)\right)^{-1} f(s) = \frac{7,83s^2+8,83s+1}{0,042105(\lambda s+1)} \tag{19}$$

4. Standard feedback controller
Subsitute Eqs. (19) and (17) into Eq. (12), we obtained Eq. (20)

$$G_{c1} = \frac{7,83s^2+8,83s+1}{0,042105\ \lambda s} \tag{20}$$

5. Determine the PID parameters according to the IMC
From Eq. (20), we can rewrite as Eq. (21)

$$G_{c1} = \left(\frac{8,83}{0,042105\ \lambda}\right)\frac{7,83s^2+8,83s+1}{8,83s} \tag{21}$$

In order to obtain K_p, T_i, and T_D, we can use Eq. (22).

$$G_{c1} = G_{PID} \tag{22}$$

Then, we obtained parameter values of PID controller from the IMC as follows:

$$K_p = \frac{8,83}{0,042105\ \lambda} \tag{23}$$

$$T_i = 8,83 \tag{24}$$

$$T_D = \frac{7,83}{T_i} \tag{25}$$

Simulations and discussions

Next, a simulation is carried out to see the results of tuning PID parameter values using the IMC method. In this study, the simulation was carried out by changing the setpoint value by 20 %. This was intended to test and evaluate how the system responds to changes in the given target. Since the value of K_p value from the IMC-PID tuning is influenced by the value of λ, the simulation also includes several λ values obtained through the trial and error method. Performance analysis of these λ values was conducted to determine the best performance. The simulation results of the PCT-14 pressure control system using the IMC-PID controller with varying λ values are shown in Fig. 7. In this paper, the proposed method is also compared to the method proposed in [1]. The comparison is demonstrade through simulation and the values of performance indices such as rise time, overshoot, settling time, steady state error, and an error index IAE. This comparison provides insight into which tuning method is better for handling set point tracking on the PCT-14 air pressure control module.

Based on the simulation results shown in Fig. 7, a performance analysis of the control system can be conducted for each value of λ. The step response characteristics of the simulation results for each value of λ are presented in Table 1.

Based on the simulation results in Fig. 7 and the analysis of transient response characteristics in Table 1, the best performance can be identified by several key factors. The absence of oscillations indicates stability, a fast rise time shows the system responds

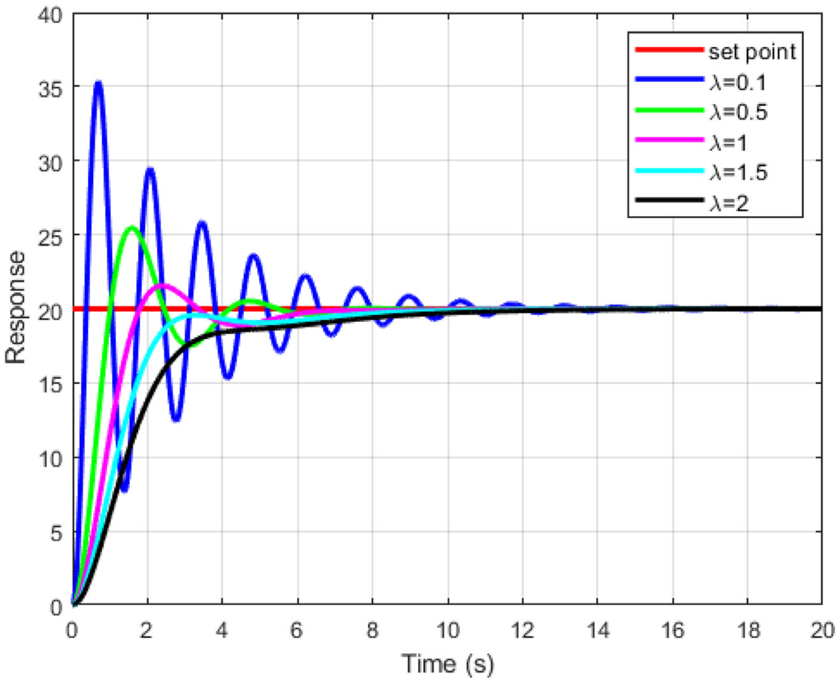

Fig. 7. Simulation of the PCT-14 air pressure control system using an IMC-PID controller with varying λ values.

Table 1
The transient response characteristics.

λ	rise time	settling time	M_p	Peak time	steady state error	IAE
0.1	0.2389	11.1055	76.65 %	0.6900	0.0179	36.47
0.5	0.6756	5.0172	27.23 %	1.5800	0.0024	20.73
1	1.1900	5.8493	7.83 %	2.3900	0.0048	23.14
1.5	1.8389	7.3996	0.03 %	20	0.0062	30.1
2	2.9012	9.0497	0.02 %	20	0.0036	40.1

quickly to changes, and a short settling time demonstrates that the system stabilizes relatively quickly. Minimal overshoot, preferably <8 %, avoids instability or overly aggressive responses. A short peak time indicates a quick reach to the first peak value, and a small steady-state error, less than or equal to 0.01, reflects the system's accuracy in achieving the desired setpoint value.

Considering these criteria, the best performance is generally achieved with a value of λ that balances these response characteristics. Based on the data presented in Table 1, $\lambda = 1$ provides a good balance with a fairly fast rise time of 1.19 s, a relatively short settling time of 5.8493 s, an overshoot of 7.83 % (which is <8 %), a peak time of 2.39 s (within acceptable limits), and a very small steady-state error of 0.0048.

However, it is important to note that the response produced by the control system for $\lambda = 1$ still exhibits overshoot. To mitigate this overshoot and an oscilation, a PID transfer function with a filter is employed. In this study, we introduce a derivative-filtered PID (PIDF) controller as an enhancement to the conventional PID controller. The derivative component of the conventional PID controller tends to amplify high-frequency harmonics, which can lead to potential instability and noise issues. To address this problem, the proposed PIDF controller incorporates a low-pass filter, effectively reducing these high-frequency disturbances [34]. For instance, G_{PID2} represents the transfer function of a PID controller with a filter [34], and the standard transfer function of the feedback controller is denoted as G_{c2}, as shown in Eqs. (26) and (27).

$$G_{PID2}(s) = K_P + \frac{K_I}{s} + K_D \frac{sN}{s+N} \tag{26}$$

K_P is the proportional gain constant, K_I is the integral gain constant, K_D is the derivative gain constant, and N is the filter coefficient. Because it uses a PIDF controller, $f(s) = \frac{1}{(\lambda s+1)^n}$ with $n = 2$ is chosen. Thus, the standard transfer function of the feedback controller is

$$G_{c2}(s) = \frac{7,83s^2 + 8,83s + 1}{0,042105\left(\lambda^2 s^2 + 2\lambda s\right)} \tag{27}$$

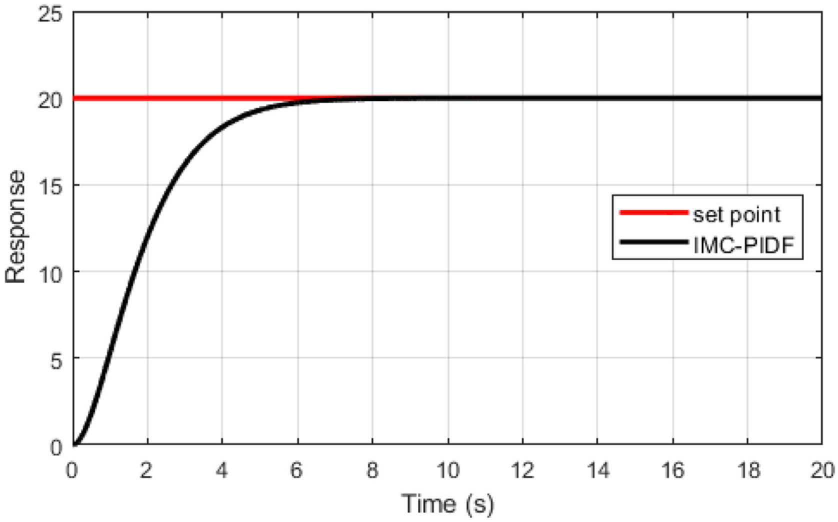

Fig. 8. Simulation of the PCT-14 air pressure control system using an IMC-PIDF controller.

Table 2
The transient response characteristics with IAE.

Controller	rise time	settling time	M_p	Peak time	steady state error	IAE
GG-PID	2,6487	nan	0	4,5	1,3049	61,37
Skogestad-PI	12,2048	nan	0,000 %	20,00	1527	88,08
IMC-PID	1,1949	5,8505	7826 %	2,3979	0.004827	23,14
IMC-PIDF	3,2584	5,6012	0,003 %	15,49	2,95E-07	40

Next, to determine K_P, K_I, K_D, and N, the following equations are used

$$G_{c2} = G_{PID2} \tag{28}$$

Thus, the IMC-PIDF control parameter values are obtained as follows:

$$\lambda = 1$$

$$N = 2$$

$$K_P = \frac{8,33}{2 * 0,042105} \approx 98,9194$$

$$K_I = \frac{1}{2 * 0,042105} \approx 11,8751$$

$$K_D = \frac{3,665}{2 * 0,042105} \approx 43,5221$$

The system simulation results with the IMC-PIDF controller as shown in Fig. 8.

As previously explained, Suharti et al. [1] applied several PID tuning methods to the PCT-14 air pressure controller module to observe the simulated response to setpoint changes. The simulations of the response produced by each tuning method indicate that the Skogestad and Good-Gain (GG) methods yield better performance compared to the Cohen-Coon (CC) and Ziegler-Nichols (ZN) methods [1]. The response simulation using the Skogestad method for the PI controller and the GG method for the PID controller on the PCT-14 air pressure controller module with a 20 % set point change can be seen in Fig. 9.

The next discussion compares the IMC-PID and the IMC-PIDF tuning results with those from [1] on the PCT-14 air pressure controller module. This comparison can be seen in Fig 10, and the performance analysis can be seen in Table 2.

Based on Fig. 10 and Table 2, IMC-PID has the fastest rise time (1.1949 s), followed by GG-PID, IMC-PIDF, and Skogestar-PI. A faster rise time indicates a quicker system response to set point changes. IMC-PIDF exhibits a very small overshoot (0.003 %), while IMC-PID also has a relatively small overshoot (7.826 %). GG-PID and Skogestad-PI have no overshoot at all, which is ideal in many cases. IMC-PID and IMC-PIDF have similar settling times (5.8505 s and 5.6012 s, respectively), which are faster compared to Skogestad-PI and GG-PID (for which settling time data is not available).

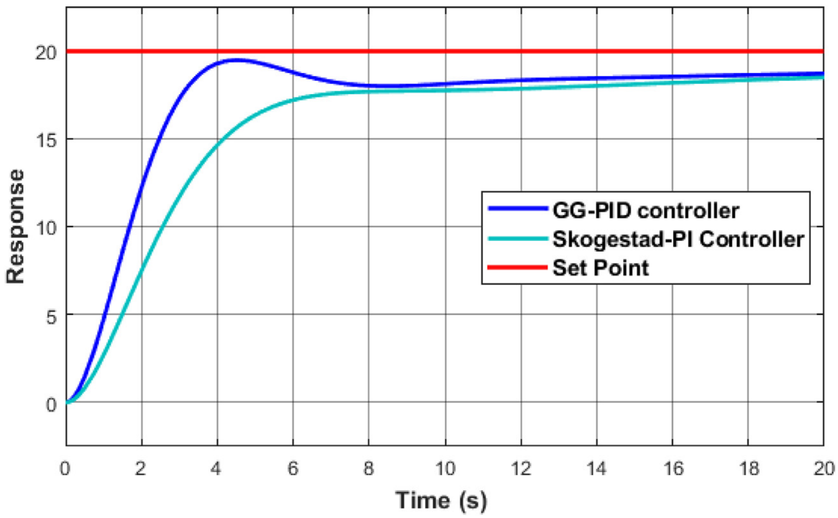

Fig. 9. The closed-loop response of the PCT-14 air pressure control system using Skogestad for the PI controller and the Good-Gain (GG) for the PID controller [1].

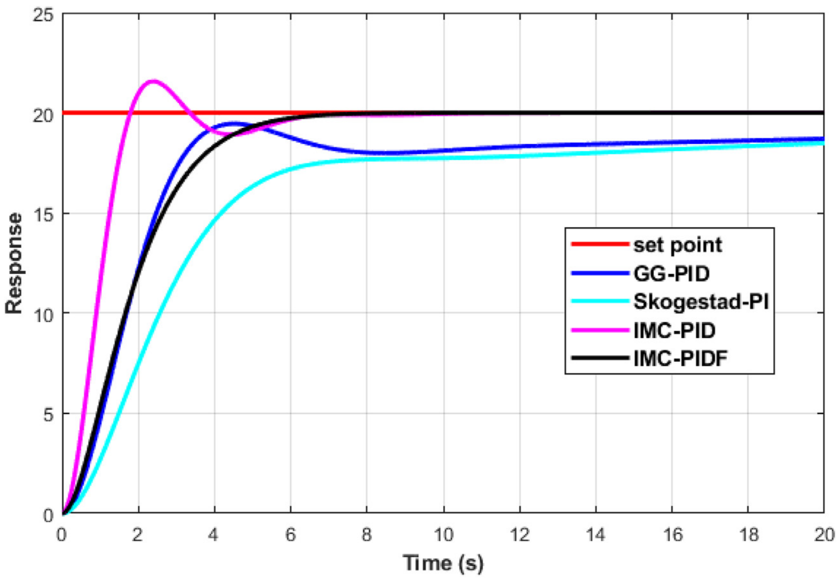

Fig. 10. Comparison of IMC-PIDF, GG-PID, Skogestad-PI, and IMC-PID Simulation Resultas in The PCT-14 Air Pressure Control System.

IMC-PIDF has the smallest steady-state error (2.945E-07), followed by IMC-PID, GG-PID, and Skogestad-PI. A smaller steady-state error indicates better accuracy. Under these conditions, the system is able to achieve and maintain the desired air pressure with high accuracy, indicating that the controller is functioning properly. The smaller the steady-state error value of the control system, the more effective the system is considered in maintaining the desired air pressure. In industrial applications requiring precise air pressure, minimizing steady-state errors is crucial to ensure that the final product meets expected specifications and quality standards. This, in turn, enhances production efficiency and reduces operational costs. The system can achieve the desired pressure while optimizing energy use, thereby decreasing energy waste and improving overall efficiency. Accurate control also reduces the system's workload, which can extend its lifespan and decrease the frequency of maintenance.

IMC-PID_has the lowest value for IAE, demonstrating the best performance in terms of integral error. Therefore, IMC-PID offers the best overall performance. Despite having a higher overshoot compared to IMC-PIDF, it excels in rise time, peak time, and exhibits very low error metric. Overall, smaller Integral of Absolute Error (IAE) values indicate that the PCT-14 air pressure control system is highly effective in reducing overall errors, thereby enhancing system efficiency, quality, and reliability.

Table 2 demonstrates that the best performance of the response system is achieved when the IMC-PID controller method is applied to handle setpoint changes. This is evidenced by the characteristics of the IMC-PID, such as rise time, settling time, peak time, steady state error, and performance index IAE which has smaller value compared to those obtained using Skogestad, GG, and IMC-PIDF for tuning the PCT-14 air pressure control module. Additionally, based on the value of IAE, smaller metric value indicates better response performance to the setpoint.

Conclusion

The performance analysis indicated that the IMC-based PID controller consistently outperforms the Good Gain-PID, Skogestad-PI, and IMC-PIDF controllers in handling set point changes. This conclusion is supported by the calculation of the Integrated Absolute Error (IAE), which showed that the IMC-PID controller achieved lower IAE value, reflecting better overall performance in minimizing absolute error over time. The findings suggest that the IMC-PID controller is more effective in managing set point changes in the PCT-14 air pressure control system. This highlights its potential application in educational settings and various industrial processes requiring precise air pressure control. The research was limited to simulations of the PCT-14′s transfer function and did not involve direct hardware testing. This may affect the generalizability of the results to real-world conditions. Future studies should focus on implementing the IMC-PID controller in actual hardware to validate the simulation results. Additionally, exploring the performance of these controllers under different operational conditions and parameter variations could provide deeper insights into their applicability and robustness. Overall, this study contributes significantly to the field of control systems by identifying the IMC-PID controller as a superior choice for air pressure control applications, providing a solid foundation for further research and practical implementations.

Limitations

The limitation of this article is that it is confined to simulation analysis of the block diagram of the PCT-14 air pressure module. The performance analysis is based only on the transfer function simulation of the control system when there is a 20 % change in the setpoint value, without any external disturbances. The control parameter values tuned using the IMC-PID method have not yet been directly tested on the PCT-14 air pressure controller module.

Ethics statements

As an expert scientist and along with co-authors of concerned field, the paper has been submitted with full responsibility, following due ethical procedure, and there is no duplicate publication, fraud, plagiarism, or concerns about animal or human experimentation.

Declaration of competing interest

The authors declare that the authors do not have competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Wahyuni Ningsih: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing, Software. **Profiyanti Hermin Suharti:** Formal analysis, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. **Mohammad Ghani:** Formal analysis, Investigation, Methodology, Software, Writing – original draft.

Data availability

No data was used for the research described in the article.

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