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# LIQUEFIED NATURAL GAS TANK PRESSURE CONTROL USING PID, PD-PI, PI-PD AND 2DOF CONTROLLERS

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## ABSTRACT

The control of the pressure of liquefied natural gas (LNG) is important for safe operation and transportation. The paper presents the control of LNG pressure in a storage tank using four controllers: PID, PD-PI, PI-PD and 2DOF. A proper tuning technique is selected to tune the controllers using a proper performance index. The step time response of the control system using the four proposed controllers is presented and the time-based characteristics are compared. The comparison reveals the best controller among the four controllers depending on a graphical and quantitative comparison study.

**KEYWORDS:** Liquefied natural gas (LNG), LNG tank pressure control, PID controller, PD-PI controller, PI-PD controller, 2DOF controller, controller tuning.

## INTRODUCTION

Liquefied Natural Gas (LNG) has great economic importance worldwise. As a fuel material all its variables (temperature, pressure and level) have to be under control. Because storage tank pressure is essential either in its lower limit or upper limit, LNG pressure control is important and has to be considered with great attention. We start by taking an idea about some of the research work regarding LNG pressure modeling and control:

Chorowski, Duda, Polinski and Skrzypacz (2015) stated that LNG must be vaporized and pressurized to a pressure compatible with the ship-engines requirements. They presented the specific technical features of the LNG system and reviewed possible flow schemes of LNG marine systems.[1] Cap, Zhang and Zou (2018) introduced a control strategy for the LNG in the insulation space in LNG carriers. They combined a nonlinear feedback technique with closed-loop gain shaping algorithm. They compared three control strategies: with nonlinear feedback, without nonlinear feedback and using 2DOF control strategies.[2] Ovidi et al. (2018) set up a computational fluid dynamics (CFD) model to analyze the dynamic behavior of LNG tanks in heavy trucks. The model allowed the prediction of the dynamic pressure built up in a damaged tank as an indication for the mechanical resistance.[3] Liu, Zhu, Zhang, Shen and Zhang (2019) analyzed the safety attachment of LNG pressure control. They obtained the minimum cut set of the safety attachment of LNG pressure control and put forward the control measures and suggestions of LNG pressure control safety accessories.[4]

Jo, Bangi, Son, Kwon and Hwang (2021) proposed the use of a model predictive control (MPC) to regulate an LNG tank pressure. They developed a dynamic model for the LNG storage tank pressure and a reduced-order model for the control purpose. They applied the offset-free MPC controller to control the tank pressure.[5] Wang, Ju and Fu (2021) developed a dynamic model to predict and investigate the performance of LNG fuel tank pressurization under marine conditions. They showed that the heat transfer between LNG vapor and tank wall dominates the pressurization process and the sloshing has severe impact on the tank pressure.[6] Sixian and Yonglin (2022) established a numerical model for phase change and external heat leakage to study the pressure variation and temperature distribution of marine LNG fuel tanks under sinusoidal sloshing excitation. They showed that when the external sloshing excitation frequency is close to the fundamental natural frequency of the LNG fuel tank, the tank pressure will drop rapidly resulting in engine shut down.[7]

Wang, Ju, Wang and Zou (2022) developed a dynamic model for a high pressure gas supply system and simulated the effects of the operating parameters on system performance. They showed that the pressure overshoot increases as the methane content decreases and the tank volume has a specific impact on the pressure response.[8] Sun, Wang, Wang, Li and Yang (2023) established a fluid-solid coupling analysis model for the dynamic response and damage of a small-scaled domed LNG storage tank under penetration and explosion conditions. They analyzed and compared the relationship of pressure at different positions of the fluid and investigated the damage characteristics of the storage tank under different conditions.[9]

**LNG Storage Tank Model for Pressure Control**

The available literature didn't have enough alternative for dynamic pressure models suitable for pressure control strategies. There is a dynamic model available used for specific controllers providing the tank pressure transfer function, $G_p(s)$ as:[2]

$$G_p(s) = 3.25\, e^{-0.25s} / [s(s-0.78)] \qquad (1)$$

The unit step time response of the tank pressure having the dynamics defined by Eq.1 is shown in Fig.1 as generated by the 'step' command of MATLAB.[10]

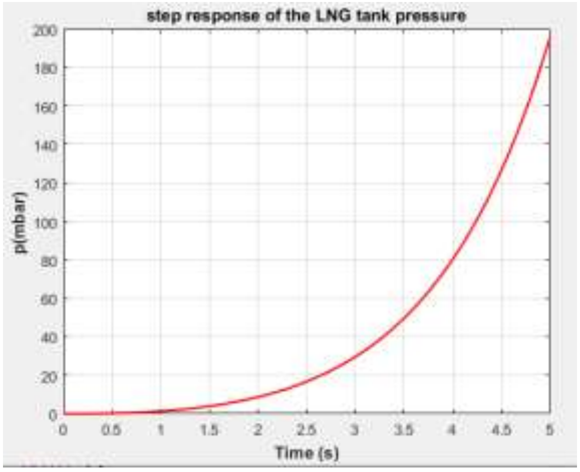


**Figure 1: Step time response of the LNG tank pressure.**

The transfer function in Eq.1 represents an unstable system which represents the first challenge of any controller or compensator because it has to stabilize the control system first incorporating the unstable process. On the other hand it has to provide good performance for the closed loop control system in terms of robustness and time-based characteristics. Moreover, the controller/compensator proposed has to provide efficient suppression for the process disturbance. This is what we are going to investigate for the four controllers investigated in this research work.

**Controlling the LNG Pressure Using a PID Controller**

The PID controller is the most used controller from the first generation of PID controllers. Even though it has some dynamic problems it is still in use up to know. To overcome the dynamic problems of PID controllers, the author introduced the second generation of PID controllers in 2014 and still investigating its application to a large class of processes with bad dynamics and instability. In this work the PID controller will be applied first to control the

LNG pressure and then three controllers from the second generation of PID controllers will be applied and investigated for performance comparison with the PID controller.

An ideal PID controller has the transfer function, $G_{PID}(s)$ given by

$G_{PID}(s) = K_{pc} + (K_i/s) + K_d s$ (2)

Where: $K_{pc}$ = proportional gain of the PID controller

$K_i$ = its integral gain

$K_d$ = its derivative gain

It has three gain parameters to be tuned for stable control system and good performance in terms of maximum overshoot and settling time. The control system incorporating a controller and the LNG pressure process with reference and disturbance inputs is shown in Fig.2. The controller with output signal U(s) and input E(s) has to satisfy the requirements of the control system with reference input R(s) and disturbance input D(s) through controller tuning.

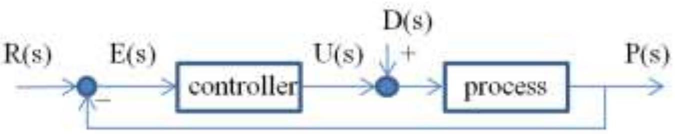


**Figure 2: Block diagram of the LNG pressure control system.**

The control system of the LNG pressure control with PID control has the closed loop transfer functions P(s)/R(s) and P(s)/D(s) using Eqs.1 (with neglected time delay) and 2 given by:

$P(s)/R(s) = N_{1R}(s)/D_{1R}(s)$ (3)

Where: $N_{1R}(s) = 3.25K_d s^2 + 3.25K_{pc}s + 3.25K_i$

$D_{1R}(s) = s^3 + (3.25K_d - 0.78)s^2 + 3.25K_{pc}s + 3.25K_i$

And $P(s)/D(s) = N_{1D}(s)/D_{1R}(s)$ (4)

Where: $N_{1D}(s) = 3.25s$

The PID controller is tuned as follows

- The unit step time response of the closed-loop control system for the reference input is evaluated using Eq.3 using the step command of MATLAB.[10]
- The optimization toolbox of MATLAB[11] is used to minimize an Integral of Time multiplied by Absolute Error (ITAE) performance index.[12]
- The tuning results for the PID controller parameters are as follows:

$K_{pc} = 5.901413$; $K_i = 93.144803$; $K_d = 962.511516$ (5)

- The unit step time response of the control system for the LNG pressure control with both reference and disturbance inputs using Eqs.3,4 and 5 is shown in Fig.3.

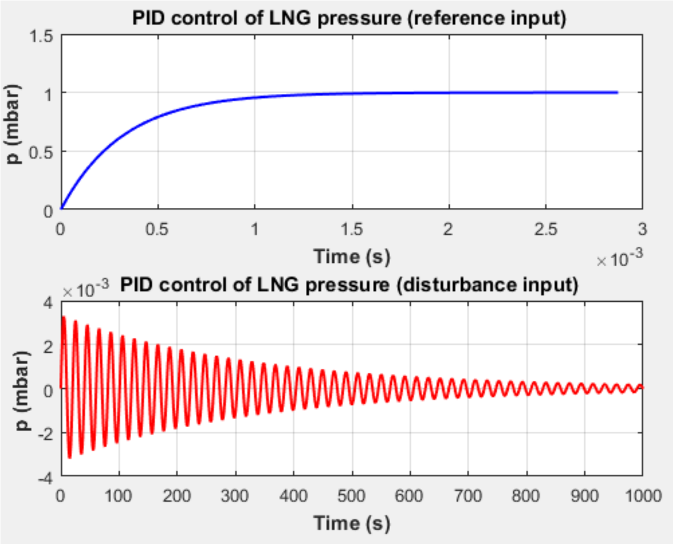


**Figure 3: PID control of the LNG pressure.**

**Comments**

- The PID controller provided a very good reference input tracking step time response. It has the following characteristics
- Maximum overshoot: 0.0125 %.
- Settling time: 0.00125 s
- The success of the PID controller regarding the reference input is faced with a failure in suppressing quickly the disturbance step time response. It has the following characteristics
- The step time response is highly oscillating.
- Maximum LNG pressure time response: 0.0033 mbar.
- Time of maximum step time response: 5 s.
- Settling time: 1600 s.

**Controlling the LNG Pressure Using a PD-PI Controller**

The PD-PI controller was introduced by the author in 2014 to control a number of difficult processes including: first-order delayed processes,[13] highly oscillating second-order process,[14] integrating plus time-delay process,[15] delayed double integrating process,[16] third-order process,[17] boost-glide rocket engine,[18] and LNG level control.[19]

The PD-PI controller is composed of two cascaded feedforward control modes: PD-mode and PI-mode. It has a transfer function $G_{PDPI}(s)$ given by[18]

$G_{PDPI}(s) = [K_d K_{pc2} s^2 + (K_d K_i + K_{pc1} K_{pc2})s + K_{pc1} K_i]/s$ (6)

Where: $K_{pc1}$ = proportional gain of the PD-control mode.

$K_d$ = derivative gain of the PD-control mode.

$K_{pc2}$ = proportional gain of the PI-control mode.

$K_i$ = integral gain of the PI-control mode.

The PD-PI controller has four gain parameters ($K_{pc1}$, $K_d$, $K_{pc2}$ and $K_i$) to be tuned to satisfy the objectives of using the controller to control the LNG pressure and provide good control system performance for reference and disturbance inputs.

The transfer function for reference input, P(s)/R(s) is given by

$P(s)/R(s) = N_{2R}(s)/D_{2R}(s)$ (7)

Where: $N_{2R}(s) = 3.25 K_d K_{pc2} s^2 + 3.25(K_d K_i + K_{pc1} K_{pc2})s + 3.25 K_{pc1} K_i$

$D_{2R}(s) = s^3 + (3.25 K_d K_{pc2} - 0.78)s^2 + 3.25(K_d K_i + K_{pc1} K_{pc2})s + 3.25 K_{pc1} K_i$

The transfer function for disturbance input, P(s)/D(s) is given by

$P(s)/D(s) = N_{2D}(s)/D_{2R}(s)$ (8)

Where: $N_{2D}(s) = 3.25s$

The PD-PI controller is tuned using the same tuning procedure used with the PID controller. The tuned parameters of the PD-PI controller are as follows

$K_{pc1} = 9.88483$, $K_d = 100.57177$

$K_{pc2} = 100.39382$, $K_i = 49.80543$ (9)

Using the closed-loop transfer function of the closed-loop control system in Eqs.7 and 8 and the PD-PI controller gains in Eq.9, the reference and disturbance input tracking unit step time response of the LNG tank-pressure is shown in Fig.4.

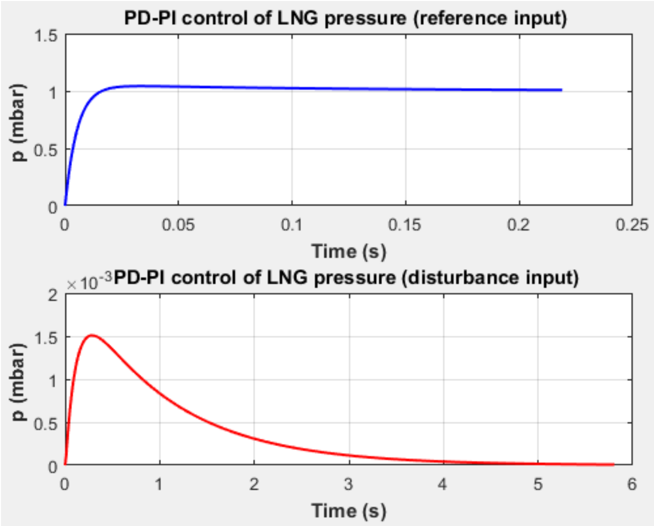


**Figure 4: PD-PI control of the LNG pressure.**

**Comments**

- ➢ The PD-PI controller provided a very good reference input tracking step time response. It has the following characteristics:
- Maximum overshoot: zero
- Settling time: 0.12 ms
- ➢ The PD-PI controller succeeded to suppress the disturbance time response. It has the following characteristics:
- Maximum LNG pressure time response: 0.0015 mbar.
- Time of maximum step time response: 0.30 s.
- Settling time: 5 s.

**Controlling the LNG Pressure Using a PI-PD Controller**

The PI-PD controller was introduced by the author in 2014 to control a number of difficult processes including: highly oscillating second-order process,[20] delayed double integrating process,[21] a third-order process,[22] coupled-dual liquid tank.[23] and fourth order blending process.[24] The block diagram of a control system incorporating a PI-PD controller and a controlled process is shown in Fig.5.[23] The controller is composed of two elements: a PI control mode element in the forward path of the block diagram and a PD control mode in a feedback loop with the controlled process. The transfer functions of the two elements of the PI-PD controller are

$G_{PI}(s) = K_{pc1}+(K_i/s)$

And $G_{PD}(s) = K_{pc2}+K_d s$ (10)

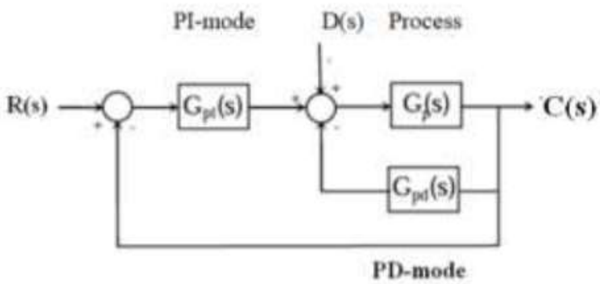


**Figure 5: Control system using a PI-PD controller.**

The transfer function for reference input using Eqs.1and 10 and the block diagram in Fig.5, P(s)/R(s) is given by

$P(s)/R(s) = N_{3R}(s)/D_{3R}(s)$ (11)

Where: $N_{3R}(s) = 3.25K_{pc1}s+3.25K_i$

$D_{3R}(s) = s^3+(3.25K_d-0.78)s^2+3.25(K_{pc1}+K_{pc2})s+3.25K_i$

The transfer function for disturbance input, P(s)/D(s) is given by:

$P(s)/D(s) = N_{3D}(s)/D_{3R}(s)$ (12)

Where: $N_{3D}(s) = 3.25s$

The PI-PD controller is tuned using the same tuning procedure used with the PID controller. The tuned parameters of the PI-PD controller are as follows:

$K_{pc1} = 33.77280$, $K_i = 36.10420$

$K_{pc2} = 22.06597$, $K_d = 11.37534$ (13)

Using the closed-loop transfer function of the closed-loop control system in Eqs.11 and 12 and the PI-PD controller gains in Eq.13, the reference and disturbance input tracking unit step time response of the LNG tank-pressure is shown in Fig.6.

**Comments**

- The PI-PD controller provided a good reference input tracking step time response. It has the following characteristics:
- Maximum overshoot: 0.863 %
- Settling time: 0.975 s
- The PI-PD controller succeeded to suppress the disturbance time response without oscillation. It has the following characteristics:
- Maximum LNG pressure time response: 0.0016 mbar.
- Time of maximum step time response: 0.065 s.

- Settling time: 120 s.

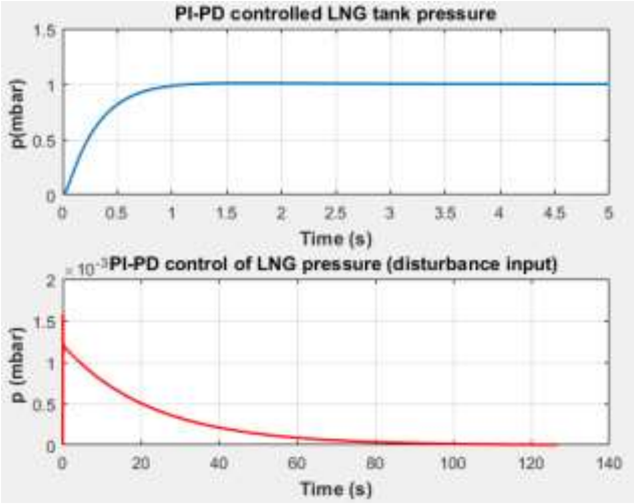


**Figure 6: LNG pressure step time response using PI-PD controller.**

**Controlling the LNG Pressure Using a 2DOF Controller**

A number of structures for the 2DOF controller were introduced by the author in 2015 to control second order processes,[25,26] greenhouse temperature[27] and a rocket engine.[28] The block diagram of one of the structures of the 2DOF controller is shown in Fig.7.[25] The 2DOF controller has two elements: A feedforward element of a transfer function $G_{c1}(s)$ receiving the reference input R(s) and a feedback element of a transfer function $G_{c2}(s)$ receiving the process output signal as shown in Fig.7. The controller has the transfer functions.

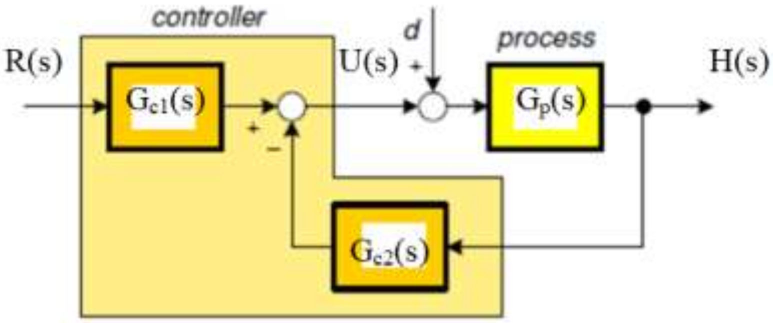


**Figure 7: Structure of a 2DOF controller.[25,29]**

$G_{c1}(s) = K_{pc1} + (K_i/s)$

And $G_{c2}(s) = K_{pc2} + (K_i/s) + K_d s$ (14)

The 2DOF controller structure shown in Fig.7 has four gain parameters to be tuned to achieve an optimal performance for the LNG pressure.

The transfer function for a reference input, [P(s)/R(s)] of the control system incorporating the 2DOF controller and the LNG tank pressure process is derived using the control system block diagram in Fig.7 and Eqs.1 and 14 and given by

$P(s)/R(s) = N_{4R}(s)/D_{4R}(s)$ (15)

Where: $N_{4R}(s) = 3.25K_{pc1}s+3.25K_i$

$D_{4R}(s) = s^3+(3.25K_d-0.78)s^2+3.25K_{pc2}s+3.25K_i$

The transfer function for disturbance input, P(s)/D(s) is given by:

$P(s)/D(s) = N_{4D}(s)/D_{4R}(s)$ (16)

Where: $N_{4D}(s) = 3.25s$

The 2DOF controller is tuned using the same tuning procedure used with the PID controller.

The tuned parameters of the 2DOF controller are as follows

$K_{pc1} = 11.37892,\quad K_i = 59.83575$

$K_{pc2} = 4.26698,\quad K_d = 14.41085$ (17)

Using the closed-loop transfer function of the closed-loop control system in Eqs.15 and 16 and the 2DOF controller gains in Eq.17, the reference and disturbance input tracking unit step time response of the LNG tank-pressure is shown in Fig.8.

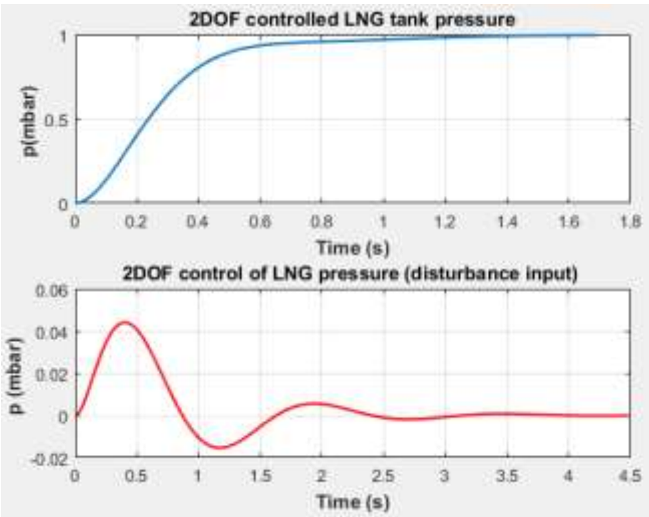


**Figure 8: LNG pressure step time response using 2DOF controller.**

### Comments

The 2DOF controller provided a good reference input tracking step time response. It has the following characteristics

- Maximum overshoot: zero
- Settling time: 1.147s

The 2DOF controller succeeded to suppress the disturbance time response with two oscillation cycles. It has the following characteristics

- Maximum LNG pressure time response: 0.044 mbar.
- Time of maximum step time response: 0.42s.
- Settling time: 4s.

### Characteristics Comparison of the Four Controllers

The characteristics comparison takes two forms: graphical and quantitative ones as follows

#### *Graphical comparison*

➢ For the reference input: The comparison is split into two graphs as illustrated in Fig.9 for PID and PD-PI in the top graph and for PI-PD and 2DOF controllers in the bottom graph.

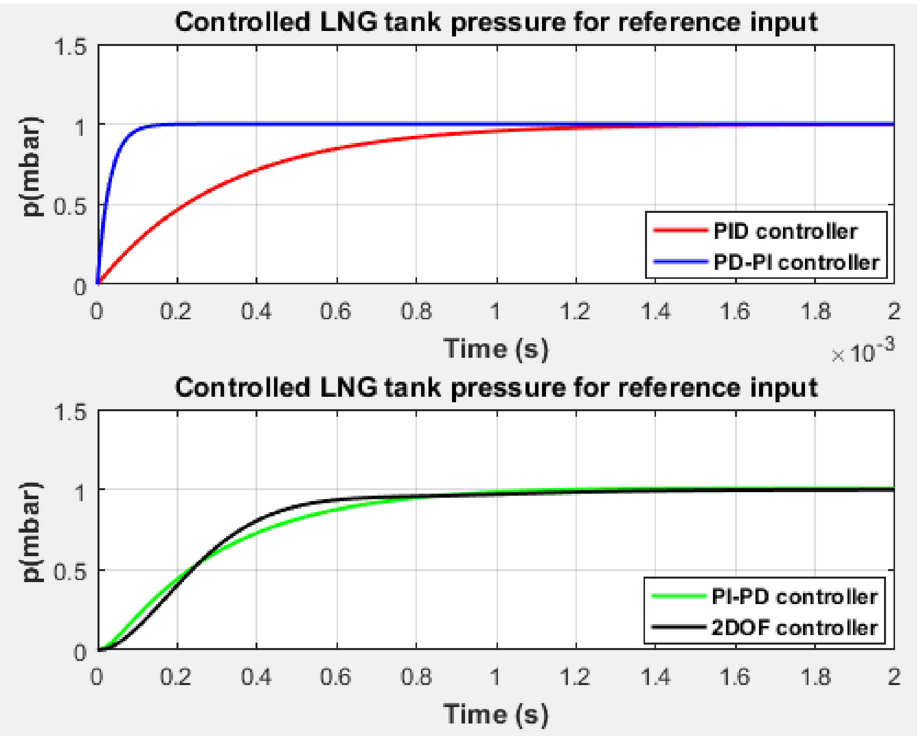


**Figure 9: Reference input step time response.**

For the disturbance input: The comparison is presented in Fig.10.

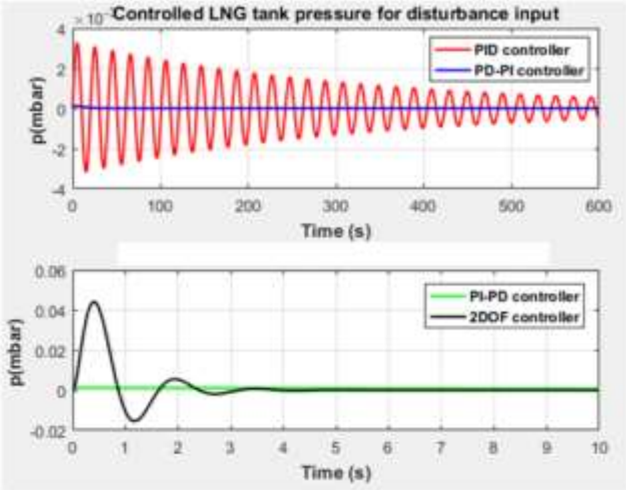


**Figure 10: Disturbance input step time response.**

*Quantitative comparison*: The time-based characteristics of the control system for the pressure control of the LNG in the transporting tank are quantitatively compared in Table 1 for reference input tracking and Table 2 for disturbance input.

**Table 1**: **Reference input time-based characteristics of the LNG pressure control using PID, PD-PI, PI-PD and 2DOF controllers.**

| Characteristics | PID controller | PD-PI controller | PI-PD controller | 2DOF controller |
|---|---|---|---|---|
| Maximum overshoot (%) | 0.0125 | 0 | 0.863 | 0 |
| Settling time (s) | 0.00125 | 0.00012 | 0.975 | 1.147 |

**Table 2**: **Disturbance input time-based characteristics of the LNG pressure control using PID, PD-PI, PI-PD and 2DOF controllers.**

| Characteristics | PID controller | PD-PI controller | PI-PD controller | 2DOF controller |
|---|---|---|---|---|
| Maximum time response (mbar) | 0.0033 | 0.0015 | 0.0016 | 0.044 |
| Time of maximum time response (mbar) | 5 | 0.30 | 0.065 | 0.42 |
| Settling time (s) | 1600 | 5 | 120 | 4 |

## CONCLUSION

- The objective of the paper was to investigate the use and tuning of PID, PD-PI, PI-PD and 2DOF controllers to control a LNG pressure in a transportation tank.

- The four controllers were tuned using the MATLAB optimization toolbox and the ITAE performance index.
- The PID controller succeeded to reduce the maximum overshoot of the reference input step time response to only 0.0125 % and succeeded to settle after 1.25 ms.
- The PID controller failed to suppress the disturbance input without oscillation and sustained 1600 s before settling.
- The PD-PI controller succeeded to eliminate completely the maximum overshoot of the control system and succeeded to settle after 0.12 ms.
- The PD-PI controller succeeded to suppress the disturbance time response and settle without oscillation after only 5 s.
- The PI-PD controller could generate reference step time response with maximum overshoot of 0.862 % and settles in less than one second.
- The PI-PD controller succeeded to suppress the disturbance step time response with only one oscillation and settles after 120 s.
- The 2DOF controller succeeded to eliminate the maximum overshoot of the control system and settles after 1.141 s.
- The 2DOF controller succeeded to suppress the disturbance step time response without any oscillation and settle after 4 s.
- The proposed PD-PI controller was the best choice recommended to control such a difficult dynamic process as depicted from Table 1, Table 2 and Figs.9 and 10.

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**BIOGRAPHY**

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