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LIQUEFIED NATURAL GAS TANK LEVEL CONTROL USING PD-PI, I-PD AND 2DOF CONTROLLERS COMPARED WITH PID CONTROL

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ABSTRACT

The control of the level of liquefied natural gas (LNG) has vital importance to maintain safe transportation and operation. The paper presents the control of the level in a storage tank using three proposed controllers: PD-PI, I-PD and 2DOF controllers. 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 three proposed controllers is presented and compared with that using a conventional PID controller from previous research work. The comparison reveals the best controller among the three controllers depending on a graphical and quantitative comparison study.

KEYWORDS: Liquefied natural gas (LNG), PD-PI controller, I-PD controller, 2DOF controller, PID controller, controller tuning.

INTRODUCTION

Natural gas is a clean source for energy and in production in many locations world wise. As a gas it occupies large volumes and required huge tanks to transport it to consumers or very expensive pipelines. The solution of this problem is to liquefy it and transfer it in tanks. For safety of the transportation problem the liquefied nature gas (LNG) variables: level, pressure and temperature has to be controlled to avoid un-safe transportation of the LNG. We start by taking an idea about some of the research work in this field.

Li, Wang and Liu (2018) outlined that an accurate detection of liquid level in LNG tanks is an important issue to insure safe and stable operation of LNG ships and a key parameter in supply and safety control systems. They used the analysis of LNG temperature under different pressures to calculate the liquid level and storage of LNG and providing more reliable basis for the calculation of energy consumption.[1] He et al.(2018) presented a method for liquid storage monitoring in LNG tanks. They suggested by supporting the LNG tank by helical springs and assumed the resulting dynamic system as a SDOF vibrating system with very simple relationship for its natural frequency from which the storage quantity (mass) can be estimated through the measurement of the tank natural frequency. Using springs with 31.5 mm length, 4.5 mm coil diameter and 4 turns provided the best results in predicting the stored quantity of the LNG.[2] Cao, Zhang and Zou (2010) investigated the pressure control of LNG in an LNG carrier using a nonlinear feedback technique and a closed-loop shaping algorithm for both reference and disturbance inputs. They used s delayed first-order + an integrating model for the pressure of the LNG in the storage tank. They compared three control strategies: with and without nonlinear feedback and 2DOF control strategies.[3] Kulor, Markus and Apprey (2019) investigated the control of gas-liquid cylindrical cyclone using MPC-PID control. They derived a 2DOF dynamic model for the level and pressure of the LNG inside the cyclone and provided a block diagram for the MPC-PID based control system. Using MATLAB, they provided the step time response for the two cyclone variables for reference and disturbance inputs.[4]

Zhao, Zhang and Li (2020) introduced a new controller to control the level of a LNG carrier tank. They used a Gaussian function to decorate nonlinearly the output of the linear controller designed by a second-order closed-loop gain-shaping algorithm. They compared the performance of the LNG level control system using their proposed controller with controller without nonlinear decoration and a PID controller. They used a transfer function for the tank level composed of a first-order pole and an integrator with very small process gain,[5] 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.[6] Liang, Zhang, Go, How and Li (2022) proposed a robust control with asymmetric barrier Lyapunov function considering predicted output constraints under unknown dynamics and external disturbances. They employed a predictor based method to deal with time delay induced by the control inputs. They verified the performance of the proposed control system through simulation.[7] Princewill, Ubasom and Chibuike (2023) reviewed works on liquefied petroleum gas (LPG) storage tanks to assess boil-off gas (BOG). They outlined that continuously evaporated LPG vapor causes the pressure inside the tank to rise due to heat entering the tank during storage and transportation.[8]

LNG Storage Tank Model for Level Control

The analysis of any control system depends on both process and controller/compensator. The LNG tank used is a Da-Peng Sun liquid tank cargo number 2 manufactured in China and its cross-section is shown in Fig.1.[9]

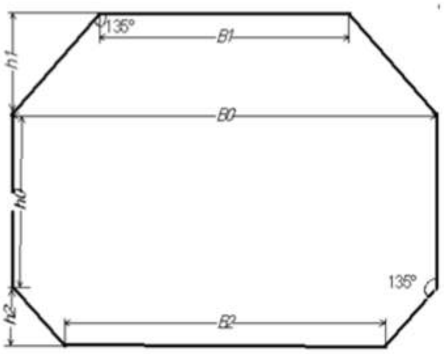

Figure 1: Cross-section of LNG Dapeng Sun tank No.2.[9]

It has the following dimensions (in m).[5,9]

$h_1 = h_0 = 17.55$; $h_2 = 3.05$

$B_0 = 35.5$; $B_1 = 23.75$; $B_2 = 29.4$

Tank full capacity: 41,747 m^3

Operating pressures inside the LNG tank for gas propelled ships ranges from 0.7 to 7 bar,[10] and the maximum allowable LNG level in the tank is 95 % of the full total filling level of the tank.[11] This means that there is a need to provide control systems to deal with the level of those two operating variables of the LNG tank. The present work deals with level control of the LNG level inside the storage tank.

The dynamics of the cargo tank of the LNG transportation for its liquid level inside the tank is defined by a transfer function, $G_p(s)$ relating the tank head H(s) and its input flow rate $Q_i(s)$ given by[5]:

$$G(s) = 0.0025 / \{s(1579.74s + 1)\} \quad (1)$$

The transfer function in Eq.1 represents an unstable system that upon receiving a step input it will not reach a steady-state value. This represents a challenge for proposed controller used to control the LNG level inside the tank. It has to stabilize the level first and secondly to provide good dynamic performance through controller tuning. The unit step time response of the LNG level is generated using MATLAB '*step*' command,[12] for the dynamic model in Eq.1 which is shown in Fig.2.

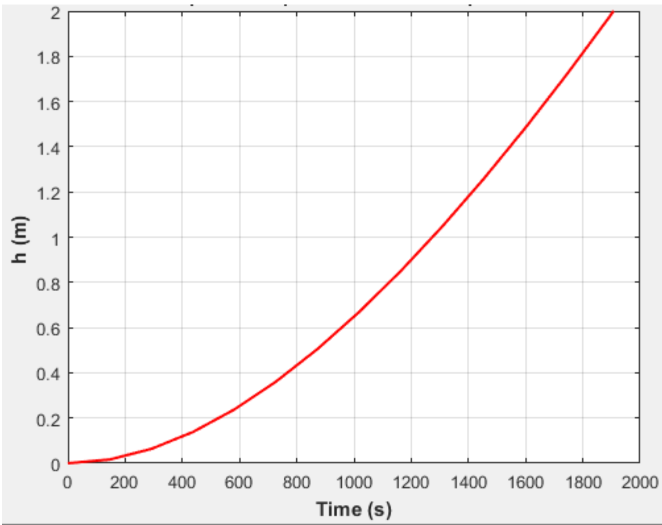

Figure 2: Step response tracking of the LNG level.

Controlling the LNG Level 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] and boost-glide rocket engine.[18]

The transfer function of the PD-PI controller, $G_{PDPI}(s)$ given by:[18]

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

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 in controlling the LNG level in the storage tank. It is tuned as follows:

- The transfer function [H(s)/R(s)] of the control system incorporating the PD-PI controller and the LNG tank level process is derived using the control system block diagram and Eqs.1 and 2 and given by:

$$H(s)/R(s) = [aK_dK_{pc2}s^2+a(K_{pc1}K_{pc2}+K_dK_i)s+aK_{pc1}K_i]/D(s) \quad (3)$$

Where:

$D(s) = bs^3+(1+aK_dK_{pc2})s^2+a(K_{pc1}K_{pc2}+K_dK_i)s+aK_{pc1}K_i$

a = 0.0025 (process parameter from Eq.1)

b = 1579.74 (process parameter from Eq.1)

- The step command 'step' of MATLAB is used to evaluate the step time response of the control system for reference input tracking.[12]
- The MATLAB optimization toolbox[19] is used to minimize an ISTSE performance index.[20]
- The tuned parameters of the PD-PI controller obtained using the above procedure are as follows:

K_{pc1} = 0.392328, K_d = 250.00135

K_{pc2} = 100.0033, K_i = -0.08281 (4)

- Using the closed-loop transfer function of the closed-loop control system in Eq.3 and the PD-PI controller gains in Eq.4, the reference input tracking unit step response of the LNG tank-level is shown in Fig.3.
- Comments:
  - The maximum overshoot is zero.
  - The settling time is 100 s.
  - The steady-state error is zero.

Controlling the LNG Level Using an I-PD Controller

The I-PD controller was introduced by the author in 2014 to control a number of difficult processes including: highly oscillating second-order process[21],[22] and a third-order process.[23] The block diagram of a control system incorporating an I-PD controller and a controlled process is shown in Fig.4.[23]

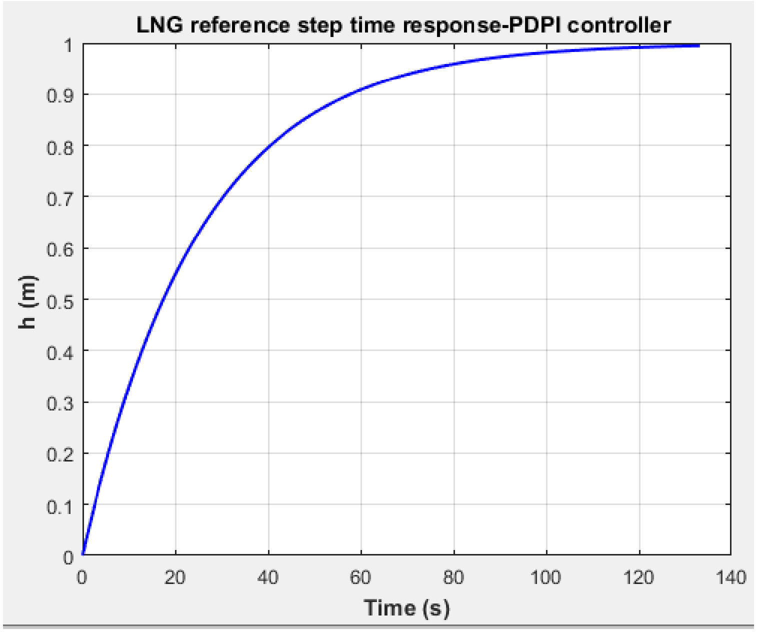

Figure 3: LNG level step time response using PD-PI controller.

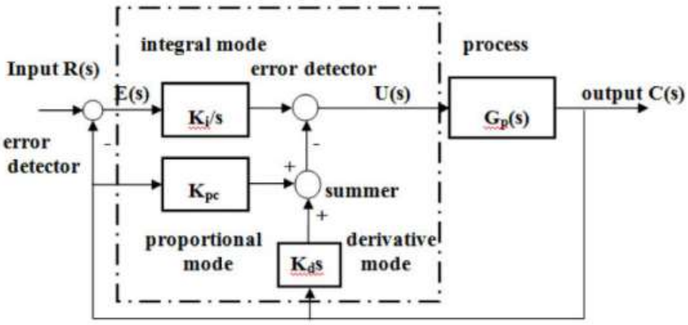

Figure 4: Control system using an I-PD controller.[23]

The transfer function of the control system using an I-PD controller for the LNG level process, H(s)/R(s) for reference input tracking is derived from the block diagram in Fig.4 and using Eq.1 of the process giving:

$$H(s)/R(s) = aK_{pc}K_i/[bs^3+(1+aK_{pc}K_d)s^2+aK_{pc}s+aK_{pc}K_i] \quad (5)$$

A and b are the process parameters given in Eq.1 and K_i, K_{pc} and K_d are the I-PD controller gain parameters. Eq.5 is used in drawing the reference tracking step time response of the control system and used in the tuning of the I-PD controller.

The I-PD controller is tuned using the MATLAB optimization toolbox[19] and the ISTSE performance index.[20] The tuned I-PD controller gain parameters are:

$$K_i = 0.00908; \quad K_{pc} = 479.9999; \quad K_d = 54.9999 \quad (6)$$

The reference input tracking step time response of the control system using the tuned I-PD controller is shown in Fig.5.

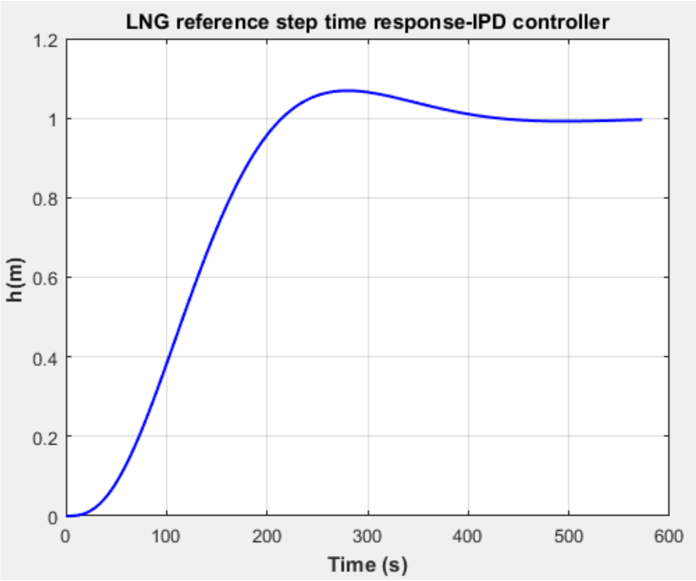

Figure 5: LNG level step time response using I-PD controller.

Comments

- The maximum overshoot is 6.9 %.
- The settling time is 380 s.
- The steady-state error is zero.

Controlling the LNG Level Using a 2DOF Controller

A number of structures for the 2DOF controller were introduced by the author in 2015 to control second order processes,[24,25] green house temperature,[26] and a rocket engine,[27] The block diagram of one of the structures of the 2DOF controller is shown in Fig.6,[24] 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.6. The controller has the transfer functions:

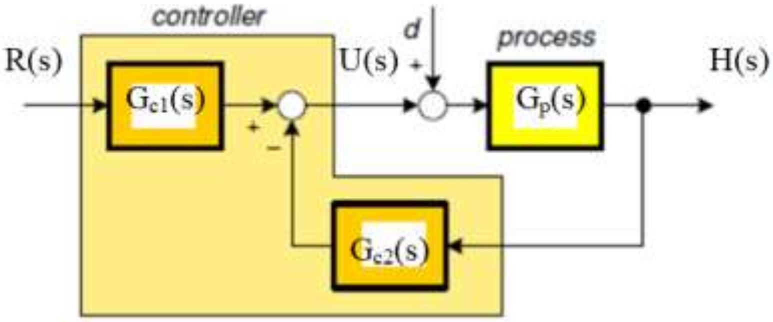

Figure 6: Structure of a 2DOF controller.[25,28]

$G_{c1}(s) = K_{pc1} + (K_i/s)$ and $G_{c2}(s) = K_{pc1} + (K_i/s)$ (7)

Where; K_{pc1} = Proportional gain of the feedforward part.

K_i = Integral gain of both controller elements.

K_{pc2} = Proportional gain of the feedback part.

The 2DOF controller structure shown in Fig.6 has three gain parameters to be tuned to achieve an optimal performance for the LNG head. It is tuned as follows:

- The transfer function [H(s)/R(s)] of the control system incorporating the 2DOF controller and the LNG tank level process is derived using the control system block diagram in Fig.6 and Eqs.1 and 7 and given by:

$H(s)/R(s) = [aK_{pc1}s+aK_i] / [bs^3+s^2+aK_{pc2}s+aK_i]$ (8)

- The step command '*step*' of MATLAB is used to evaluate the step time response of the control system for reference input tracking.[12]
- The MATLAB optimization toolbox.[19] is used to minimize an ISTSE performance index.[20]
- The tuned parameters of the 2DOF controller obtained using the above procedure are as follows:

$K_{pc1} = 6.5545$, $K_i = 0.54894$

$K_{pc2} = 956.9997$ (9)

- Using the closed-loop transfer function of the closed-loop control system in Eq.8 and the 2DOF controller gains in Eq.9, the reference input tracking unit step response of the LNG tank-level is shown in Fig.7.

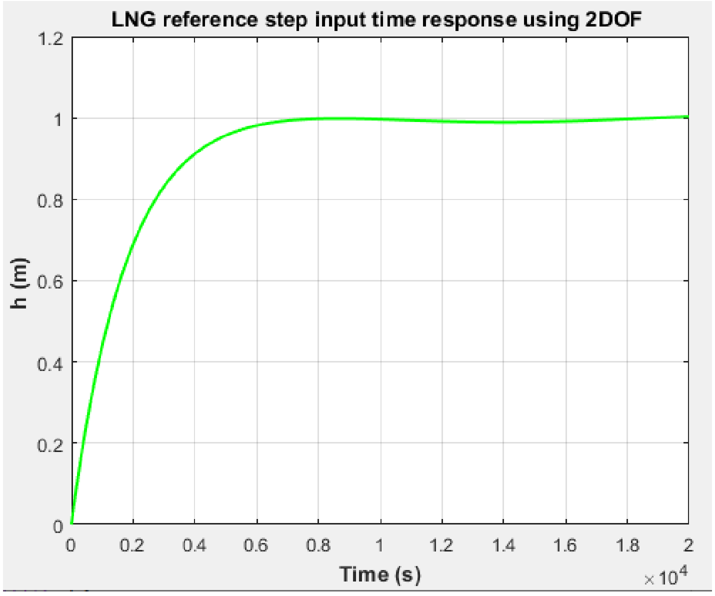

Figure 7: LNG level step time response using 2DOF controller.

Comments

- The maximum overshoot is zero.
- The settling time is 5930 s.
- The steady-state error is zero.

Comparison with PID controller

The effectiveness of the proposed controllers is investigated through comparison with a PID controller used to control the same process,[5] The comparison takes two forms: graphical and quantitative ones as follows:

- *Graphical comparison*: It was planned to compare all the step time responses of the three proposed controllers besides the PID controller. This was difficult because of the large difference in the response range. Therefore, I split the comparison to two graphs as illustrated in Fig.8 for PD-PI and I-PD controllers and Fig.9 for 2DOF and PID controllers.

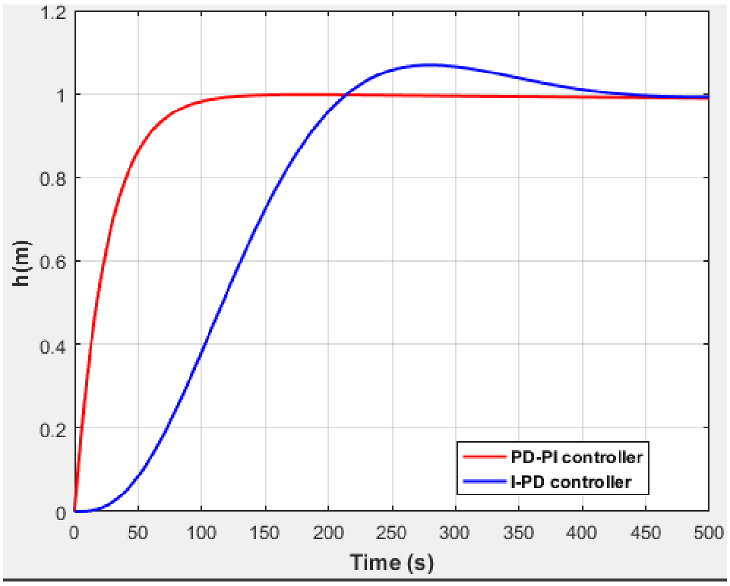

Figure 8: Step response tracking with PD-PI and I-PD controllers.

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

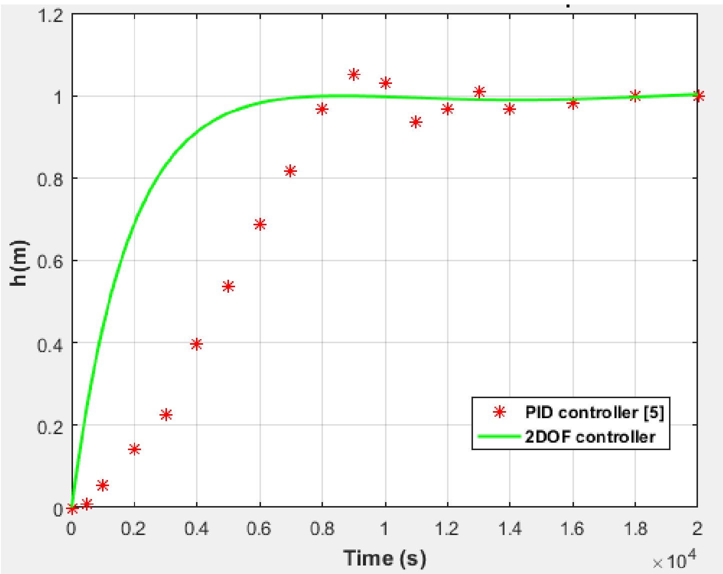

Figure 9: Step response tracking with 2DOF and PID controllers.

Table 1: **Time-based characteristics of the LNG level control using PD-PI, I-PD, 2DOF and PID controllers.**

Characteristics	PD-PI controller	I-PD controller	2DOF controller	PID controller
Maximum percentage overshoot (%)	0	6.9	0	5.3
Settling time (s)	100	380	5930	16000
Steady-state error	0	0	0	0

CONCLUSION

- The objective of the paper was to investigate the use and tuning of PD-PI, I-PD and 2DOF controllers to control a LNG level in a transportation tank.
- The three controllers were tuned using the MATLAB optimization toolbox and the ISTSE performance index.
- The PD-PI controller succeeded to eliminate the maximum overshoot of the control system compared with 5.3% for the PID controller.
- The PD-PI controller succeeded to settle after 100 s compared with 16000 s for the PID controller.
- The I-PD controller could not eliminate the maximum overshoot of the control system. It provided a maximum overshoot 30.2% more than that of the PID controller.
- The I-PD controller succeeded to settle after 380 s compared with 16000 s for the PID controller.
- The 2DOF controller succeeded to eliminate the maximum overshoot of the control system compared with 5.3% for the PID controller.
- The 2DOF controller succeeded to settle after 5930 s compared with 16000 s for the PID controller.
- The controlled process had a difficult dynamic model: un-stability and very large difference between its parameters. This made the effort to tune the proposed controllers very awkward.
- The proposed PD-PI controller was the best choice recommended to control such a difficult dynamic process as depicted from Table 1 and Figs.8 and 9.

REFERENCES

1. R. Li, G. Wang and C. Liu “Study on calculation of liquid level and storage of tanks for LNG-fuel vessels”, LOP Conference Series: Earth Environmental Science, 2018; 111: 012030, 9.
2. H. He et al, “Monitoring and analysis of liquid storage in LNG tank based on different supporting springs”, AIP Conference Proceeding, Vol.1955, ID: 030058, 2018; 4.
3. J. Cao, X. Zhang and X. Zou, “Pressure control of insulation space for liquefied natural gas carrier with nonlinear feedback technique”. Journal of Marine Science and Engineering, 2018; 6: 133, 11.
4. F. Kulor, E. Markus and M. Apprey, “MPC-PID control of a gas liquid cylindrical cyclone”, International Journal of Mechanical Engineering and Robotics Research, 2019; 8(4): 639-645.
5. Z. Zhao, X. Zhang and Z. Li, “Tank level control of liquefied natural gas carrier based on Gaussian function nonlinear decoration”, Journal of Marine Science and Engineering, 2020; 8: 695: 12.
6. Y. Jo, M. Bangi, S. Son, J. Kwon and S. Hwang, “Dynamic modeling and offset-free predictive control of LNG tank”. Fuel, 2021; 285, ID: 119074, 15.
7. X. Liang, Y. Zhang, S. Ge, B. How and D. Li, “Dynamic model for LNG carrier with output constraints”. IET Control Theory & Applications, 2022; 16: 729-740.
8. N. Princewill, K. Ubrasom and O. Chibuike, “Liquefied petroleum gas (LPG) storage tanks boil-off gas generation and management-review”, International Journal of Advanced Science and Engineering, 2023; 10(1): 3294-3303.
9. Z. Zang, X. Zhang and I. Cao, “Discharging part of LNG liquid cargo handling simulator”, Research Journal of Applied Sciences, Engineering and Technology, 2013; 6(21): 3978-3985.
10. M. Chorowski, P. Duba, J. Polinski and J. Skzypacz, “LNQ systems for natural gas propeller ships”, IOP Conference Series: Materials Science and Engineering, 2015; 101, 012089: 8.
11. Mathworks, “Step response of dynamic system”, https://www.mathworks.com/help /ident/ref/dynamicsystem.step.html, 2023.
12. G. A. Hassaan, “A novel feedback PD compensator used with underdamped second order processes”, International Journal of Mechanical Engineering, 2014; 4(2): 1-10.

13. G. A. Hassaan, "A novel feedback PD compensator used with a third order process", International Journal of Advanced Research in Computer Science and Technology, 2014; 2(3): 190-193.
14. C. P. Lopez, MATLAB optimization techniques, Apress, 2014.
15. Mathworks,
16. G. A. Hassaan, "Tuning of PD-PI controller used with first-order delayed process", *International Journal of Engineering Research and Technology*, 2014; 3(4): 51-55.
17. G. A. Hassaan, "Tuning of PD-PI controller used with a highly oscillating second-order process", *International Journal of Science and Technology Research*, 2014; 3(7): 145-147.
18. G. A. Hassaan, "Tuning of PD-PI controller used with an integrating plus time delay process", *International Journal of Scientific & Technical Research*, 2014; 3(9): 309-313.
19. G. A. Hassaan, "Controller tuning for disturbance rejection associated with delayed double integrator process, Part I: PD-PI controller", *International Journal of Computer Techniques*, 2015; 2(3): 110-115.
20. G. A. Hassaan, "Tuning of PD-PI controller used with a third-order process", *International Journal of Application or Innovation in Engineering Management*, 2020; 9(8): 6-12.
21. G. A. Hassaan, "Control of a boost-glide rocket engine using PD-PI, PI-PD and 2DOF controllers", *International Journal of Research Publication and Reviews*, 2023; 4(11): 913-923.
22. N. Foster, "MATLAB optimization functions and examples", Revaluation Books, 2016.
23. M. Mermoud and R. Prieto, "Performance index for quality response of dynamical systems", ISA Transactions, 2004; 43(1): 133-151.
24. G. A. Hassaan, "Tuning of an I-PD controller used with a highly oscillating second-order process", International Journal of Mechanical Engineering and Technology, 2014; 5(5): 115-121.
25. G. A. Hassaan, "Tuning of a modified I-PD controller used with a highly oscillating second-order-like process", International Journal of Computer Techniques, 2019; 6(1): 26-31.
26. M. R. Mohammed and G. A. Hassaan, "Tuning of an I-PD controller for use with a third-order oscillating process", ibid, 2020; 7(4): 1-6.

27. G. A. Hassaan, "Tuning of a 2DOF controller used with a highly oscillating second-order-like process", International Journal of Modern Trends in Engineering and Research, 2015; 2(8): 292-298.
28. G. A. Hassaan, "Tuning of a 2DOF PI-PID controller used with second-order-like process", International Journal of Computer Techniques, 2018; 5(5): 67-73.
29. G. A. Hassaan, "Temperature control of a greenhouse using PD-PI, PI-PD and 2DOF controllers", International Journal of Engineering Innovations, 2023; 12(9): 156-167.
30. G. A. Hassaan, "Control of a boast-glide rocket engine using PD-PI, PI-PD and 2DOF controllers", International Journal of Research Publication and Reviews, 2023; 4(11): 913-923.
31. D. Viancic, S. Strmcnik, M. Huba and P. Oliveira, "Comparison of some tuning methods for integrating processes", 9th International Ph.D. Workshop on Systems and Control, Izola, Slovenia, 2008; 6: 1-3.

BIOGRAPHY

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