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Liquid Level Control in Nonlinear Conical Tank using FO-PID Controller

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***Abstract*— Conical tank systems are frequently employed in operations requiring efficient liquid mixing, storage, and discharge. Their tapered structure makes it easier to regulate material flow, which lowers the possibility of silt buildup and guarantees even mixing. Because of the design and dynamic behavior of conical tanks, controlling the liquid level poses several difficulties. The tank's cross-sectional area fluctuates as liquid level changes, affecting the relationship between the liquid height and volume. A fractional order PID controller is suggested in this study to regulate the liquid level in the nonlinear conical tank system. The liquid level in the tank can be controlled by the input flow. Traditional PID controllers are widely applied but have certain limitations in properly handling such nonlinearities.**

In the FO-PID controller, fractional-order differentiation and integration have been introduced, which offers more flexibility and accuracy in comparison to a traditional PID and makes it well-suited to handle system nonlinearities. Particle Swarm Optimization, an evolutionary approach for control parameter optimization, is also incorporated. By effectively managing the intricate, non-linear search space of FOPID tuning, this method outperforms traditional techniques in terms of control performance.

***Keywords*— Fractional order PID controller, PSO, controller performance**

I. INTRODUCTION

The dynamic behavior and change in cross-sectional area of nonlinear tank systems, like conical tanks, make it difficult to regulate the liquid level. Several methods for dealing with nonlinearities have been developed over the years, ranging from traditional PID controllers to advanced model-based and optimization-driven solutions. [1] A Q-learning-based smart controller to manage liquid levels in nonlinear conical tanks by modeling the system as a Markov Decision Process (MDP). The controller, implemented in real-time with MATLAB, optimized inflow control through iterative learning without prior environmental knowledge. [2] PSO and WOA algorithms were used to optimize a fractional-order internal model controller (FOMIC) for nonlinear conical tank systems. FOIMC achieved 35-40% faster rise times, 80% reduced settling times, and eliminated overshoot compared to traditional controllers. [3] A Self-tuning fuzzy-PID controller for connected tank systems that manually modifies PID parameters using heuristic-based self-tuning. [4] A neural network-based augmentation of PID controllers for nonlinear processes in which the network dynamically adjusts PID parameters using input-output process data to ensure adaptive and efficient control. [5] For spherical tank systems, a hybrid method combining Feedback Artificial Tree (FAT) and Chaotic Henry Gas Solubility Optimisation (CHGSO) approaches with a fractional order PID controller is suggested. [6] A gain scheduled PI controller is used to control the behaviour of two-tank spherical interacting system. Here a transfer function is used to represent the systems dynamics. In order to maintain the stability of system, PI gains are adjusted by the controller in real-time.

II. PROPOSED IDEA

The proposed idea focuses on controlling the conical tank's nonlinearity by developing a Fractional Order PID controller. Unlike conventional methods, a multi-model approach is used in this proposed method where the tank's operational range is divided into linear areas in order to examine its nonlinear dynamics also ensure accuracy. The open and closed loop responses of the conical tank are analyzed. The FOPID controller parameters are analyzed and tuned using Particle Swarm Optimization (PSO). The PSO technique helps minimize the performance matrices - Integral of Square Error (ISE), Integral of Absolute Error (IAE), Integral of time absolute error (ITAE) – by selecting the optimal parameter set after multiple iterations. Comparing the FOPID controller to a traditional PID controller, we hope to evaluate the performance of them and assess how well it regulates tank levels.

III. EXISTING METHODOLOGY

- Model Predictive Control (MPC): MPC optimizes control actions by predicting future system behavior based on a model, handling constraints and optimizing performance over a prediction horizon. Its limitation lies in the need for an accurate system model, which may be challenging to derive for a non-linear conical tank, and it is computationally expensive, making real-time implementation difficult.
- Sliding Mode Control (SMC): SMC forces the system state to move along a defined surface, ensuring robustness against disturbances and model uncertainties. The limitation is the potential for chattering (high-frequency oscillations), which can affect system performance and cause wear in physical components unless properly tuned.
- Linear Quadratic Regulator (LQR) Control: For linearized systems, to minimize the cost function LQR control strategy is used. The demerit in it is that linear system models are required here but it will not effectively reflect the non-linear tank dynamics.

IV. MATERIALS

A. MATLAB

In this study, MATLAB, which supports various engineering applications is used. The toolkit of MATLAB helps in developing algorithms, analyzing data and visualizing them. It is used in various applications like machine learning, control system design and signal processing. Here MATLAB is used to analyze the real-time data from non-linear conical tank system and further helps in designing the controller for it.

B. DAQ

A microcontroller-based Data Acquisition Card is used in this approach to ensure data flow with physical sensors and actuators. The DAQ system used here in MATLAB provides efficient interaction between the control algorithm and the conical tank system. The DAQ receives sensor output which is analog and converts it into digital signal. Then through serial communication the data is sent to Simulink, and the control algorithm processes the data. Again, the processed data is sent through DAQ to actuators like pumps or valves.

MATLAB Simulink makes it easier for integration and supports real time testing and implementation of the controller with conical tank system.

C. DPT(Level Transmitter)

In this study, we use pressure transmitter of Allen Bradley.

By measuring the pressure difference between two points, we can calculate the liquid level of the conical tank system. One point is the tank's bottom, and the other is the reference point either the top or atmosphere. Based on the hydrostatic pressure principle, pressure at the bottom of the tank is proportional to the density and height of the conical tank's liquid column. The liquid level is indicated by the electrical signal(4-20mA) which is the pressure difference obtained by from the transmitter. The transmitter's output is sent to the DAQ system i.e. ATMega2560, which processes the signal and uses it in the control algorithm to regulate the tank's level.

D. CONTROL VALVE

The control valve that is used here has 4-20mA input range and is employed for regulating the flow. The electrical signal is converted into a pressurized signal of range 3-15 psi to actuate the control valve. This helps in regulating the flow rates of fluid or gas in various industrial applications. Hence the ability of the device to convert the electrical signal into mechanical movement for controlling the flow is significant for maintaining optimal process conditions.

TABLE 1.1

COMPONENTS	SPECIFICATION
Differential Pressure Transmitter (DPT)	Input-24V Output – (4-20mA)
Digital ammeter	Measuring range(4-20mA) DC
Data Acquisition Card (DAQ)	Operating range(5V)
Control Valve	Input current(4-20mA) and output pressure(3-15psi)

V. SYSTEM DESCRIPTION

A. FIGURE

Fig. 1.1 Conical tank system

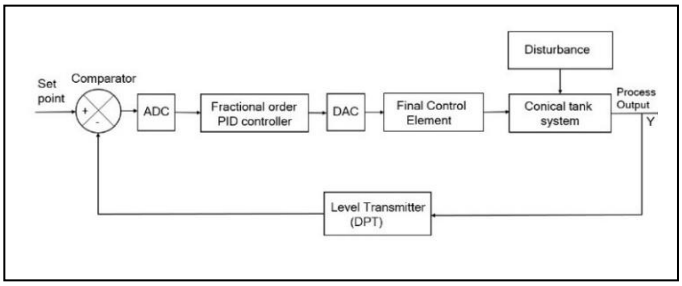
A fractional order PID controller should be used to maintain the liquid level in the conical tank. In this case, the inflow into the tank is considered the manipulated variable, while the level is considered the control variable. The following are the tank's specifications. The Conical Tank taken for the experiment is made up of material SS316 (Stainless Steel).

TABLE 1.2

S.No	Parts/Field instruments	Specifications/Description
1	Conical tank	SS316 is the material. Height: 60cm, Thickness: 0.2cm, Upper diameter: 35cm, Bottom diameter: 5cm
2	Level transmitter	Source: Rosemount, Type: DPT 24 DC at 200mA is the supply range; 0-4000 mmWc is the measuring range and 4-20mA is the output range for a two-wire system.
3	Rotameter	Teleline is the material, Flow range: 40-440 LPH, End connection is ¼” BSP(F). Thread, stainless steel for the float, and acrylic for the body.
4	Pneumatic Control Valve	Type: Globe valve, Source: RK valve Ltd., Flow rate: 500/1000 litres per hour, Trim mat: SS316, Action of the valve: Air to open, Medium: Water/Air
5	Reservoir Tank	Length: 60cm, Width: 30cm, Height: 30cm, Thickness: 0.15cm, Material - SS316

B. BLOCK DIAGRAM

Fig. 1.2 FOPID Block Diagram



The nonlinear conical tank system is taken into consideration. The live system is formed by a closed loop of conical tank, reservoir and water pump. A personal computer that serves as the controller, a differential pressure transmitter (DPT), a current pressure converter, and a DAQ card all help. By sending the control signal to an I/P converter via digital to an analog converter (DAC), the stem position of the pneumatic valve is controlled, hence regulating the inlet to the conical tank. The valve position regulation operates between 4 and 20mA which translates to 3 to 15psi of compressed air pressure. DPT is used to measure the tank’s water level, and the output current, which ranges from 4 to 20mA, is then sent to the control system using an analog to digital converter (ADC).

C. OPERATIONAL WORKING

The system's non-linearity arises from the varying flow area of the tank with liquid height. A differential pressure transmitter monitors the liquid level by detecting the hydrostatic pressure difference, converting it into an electrical signal proportional to the liquid height. This signal is transmitted to the ATMega2560 microcontroller, which is a DAQ system, converting the analog signal to digital and transmitting it to MATLAB Simulink via serial communication. In Simulink, the data is processed by a FOPID controller, which uses fractional orders for integral, and derivative actions to enhance control flexibility. Particle Swarm Optimization (PSO) is used for optimizing the controller variables in order to lower performance indices like ISE, IAE and ITAE. Simulink's regulation signal is sent back to the ATMega2560, which drives control elements such as pumps or motorized valves to regulate inflow or outflow and maintain the desired liquid level. Real-time monitoring and validation are conducted through open-loop and closed-loop tests, comparing the FOPID controller's performance to a typical PID controller.

D. FOPID Controller:

The proportional(P), integral(I) and derivative(D) terms in a traditional PID controller have integer ordering (0, 1, -1). Nevertheless, the FOPID controller permits non-integer(fractional) orders for the integral and derivative terms, denoted by λ and μ.
The FOPID controller formula can be expressed as: $U(s)=Kp\cdot E(s)+Ki\cdot s^{-\lambda}\cdot E(s)+Kd\cdot s^{\mu}\cdot E(s)$
Where,
Kp: Proportional gain
Ki: Integral gain
Kd: Derivative gain
$s^{-\lambda}$: Fractional integral term with order λ
s^{μ}: Fractional derivative term with order μ

E. OPTIMIZATION OF FOPID CONTROLLER - PARTICLE SWARM OPTIMIZATION (PSO)

The evolutionary optimization technique known as Particle Swarm Optimization (PSO) was inspired by the social behavior of fish schools and flocks of birds. It is particularly effective for optimizing complex, nonlinear, and high-dimensional problems, making it suitable for tuning Fractional Order Proportional-Integral-Derivative (FOPID) regulator variables. PSO can be used to find the most suitable values of the FOPID control settings—namely Kp, Ki, Kd , and the fractional orders λ and μ—to achieve the best possible control performance for this nonlinear conical tank systems.

- Objective Function: Minimize performance metrics (IAE, ISE, ITAE).
- Swarm Initialization: Randomly initialize particles representing FOPID parameters – position, velocity, swarm.
- Fitness Evaluation: Evaluate the controller's performance for each particle.
- Update Velocity & Position: Move particles based on best positions. Iterate to find the optimal parameters.
- Convergence: Select the best parameter set after iterations.

F. OPEN LOOP RESPONSE

The initial open-loop output transfer function is first obtained, and this control strategy is based on the inference that the plant can be modeled by a transfer function of initial order plus a system delay (FOTFPTD), described as
$G(s) = K.e-Ls /(1 + sT)$

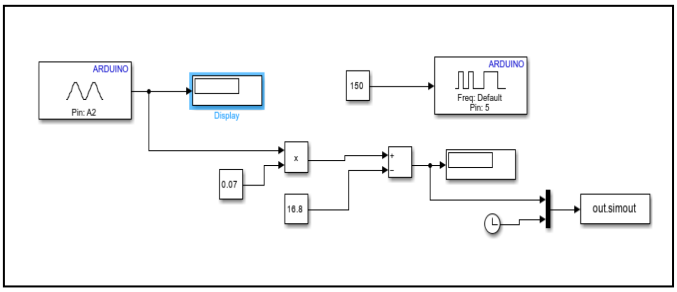


Fig. 1.3 Real -Time Open Loop Simulink Model

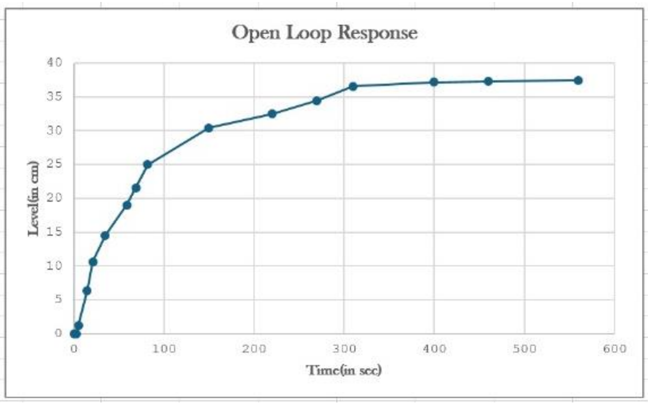


Fig. 1.4 Real- Time Open loop response graph

Using MATLAB's system identification tool, the system's input-output relationship is ascertained as follows:

$$G(s) = \frac{0.009003}{23.384s + 1} e^{-3s}$$

K (Process Gain) = 0.009003
T (Time constant) = 23.384 sec
L (Dead time) = 3 sec

VI. RESULT AND CONCLUSION

Thus, by using MATLAB Simulink model the conical tank systems open loop response has been successfully obtained, providing valuable data for modeling the dynamic behavior of this process. Since the conical tank system exhibits significant nonlinearity due to its changing cross- sectional area, a single model may not fully capture its dynamics. Therefore, a multi-model approach is adopted, where multiple models represent different operating regions of the system. This approach allows a more accurate representation of the tank's nonlinear behavior, enhancing us understanding of its dynamics and providing a strong foundation for effective control. The FOPID controller, with its fractional derivative and integral orders, offers greater flexibility and tuning capability compared to conventional PID controller, allowing it to handle complex dynamics of the nonlinear system more effectively. The Particle Swarm Optimization (PSO) technique is used to optimize the FOPID tuning variables, which include proportional gain, integral gain, derivative gain, and fractional orders of integration and differentiation. This optimization approach ultimately results in a robust and efficient control system for the conical tank, addressing the complexities of the process and achieving stable, accurate level control.

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