Simulation-Based Modeling and Control of an Industrial Pump System with Robustness Analysis Under Uncertainty and Overload Conditions

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Abstract

Industrial pump systems are widely used in wastewater treatment and industrial water handling applications, where improper operation and limited user knowledge of system parameters often lead to operation beyond normal operating limits. Such conditions can result in degraded performance and an increased risk of system instability. This study presents a simulation-based modeling and control framework designed to evaluate the robustness of an industrial pump system under uncertain and degraded operating conditions. A dynamic model of the pump system was developed using MATLAB/Simulink and controlled using proportional–integral (PI) and proportional–integral–derivative (PID) control strategies. Controller performance was evaluated under nominal conditions, parameter variations, external disturbances, and extended overload operating scenarios to assess system stability and performance under high-stress conditions. Key performance metrics, including rise time, settling time, overshoot, and steady-state error, were analyzed to compare controller robustness. The results indicate that the designed control system maintains stability and acceptable performance under high-stress conditions. This work serves as an academic exercise in system modeling, control design, and robustness analysis, providing practical insight into the behavior of industrial pump systems under non-ideal operating conditions.

Introduction

Industrial pump systems are widely used in wastewater treatment, industrial water management, and environmental applications. Reliable pump operation is critical to maintaining continuous system performance, ensuring safety, and meeting relevant industry standards. In many industrial plants, pumps must operate under uncertain conditions and varying load demands, which makes effective control an essentials part of system design and operation. As a result, pump system modeling and control have become important topics in both academic research and industrial practice.

Although industrial pump systems are commonly used, they are often operated beyond the assumed standard condition during the original design stage. In real-world applications, limited user knowledge of system parameters, combined with uncertain operating demands, can lead to overload operation that exceeds the intended limits. Longer operating hours, increased input rates, and unexpected external disruptions may cause parameter changes and degraded system behavior, increasing the risk of instability or reduced performance. These issues emphasize the need to evaluate pump control systems not only under ideal conditions, but also under practical and challenging scenarios.

Most industrial control design approaches focus on nominal system models and standard operating conditions, which may not fully represent the uncertainties and disturbances encountered in real-world environments. While proportional–integral (PI) and proportional–integral–derivative (PID) controllers are widely applied due to their simplicity and proven effectiveness, their robustness under time-varying parameters, external disruptions, and overload conditions is not always precisely evaluated. As a result, a gap exists between the theoretically predicted controller performance and the actual system behavior under high-stress operating conditions.

The objective of this study is to address this gap by presenting a simulation-based modeling and control framework for evaluating the robustness of an industrial pump system. A dynamic model of the pump system is developed using MATLAB/Simulink, and PI/PID control systems are implemented and analyzed. System performance is evaluated under nominal conditions, parameter variations, external disruptions, and extended overload operating scenarios. By examining key performance metrics such as rise time, settling time, overshoot, and steady-state error, this study aims to provide insight into the stability limits and performance constraints relevant to real-world pump operation.

System Modelling

2.1 Pump System Description

The industrial pump system described in this study represents a simplified model of an electric motor-driven industrial pump commonly found in wastewater treatment and industrial water management application. The primary objective of the pump is to regulate output flow rate in response to varying operating demands. In practical installations, these pump systems are vulnerable to load fluctuations, shifting inflow conditions, and external disturbances, which can have a substantial influence on their dynamic response.

The pump system is designed at a functional level rather than a detailed physical component level in order to concentrate on control performance and robustness analysis. This modeling technique maintains a level of complexity appropriate for control design and simulation-based evaluation while capturing the system's fundamental dynamic features.

2.2 Modelling Assumptions

Several assumptions were made to simplify the modeling process while maintaining the essentials of the control analysis. First, the pump and motor assembly is presumed to be in an ideal condition and operate within normal mechanical limits, and mechanical nonlinearities such as shaft elasticity and bearing friction are neglected. Second, fluid properties are assumed to remain constant during the simulation, and effects such as cavitation and temperature-dependent viscosity variations are not considered. Third, sensor and actuator dynamics are assumed to be sufficiently fast relative to the dominant system dynamics and are therefore neglected.

These assumptions allow for the creation of a practical dynamic model appropriate for robustness assessment under uncertain and varying operating conditions and are consistent with widely used modeling techniques for control-oriented analysis.

2.3 Dynamic Model Formulation

The pump system is modeled using a linear time-invariant first-order plus dead-time (FOPDT) model, which captures the dominant slow dynamics of many flow-related industrial processes while remaining appropriate for controller design and robustness testing. The nominal plant is defined as

$$G(s) = \frac{K}{\tau s + 1} e^{-Ls}$$

where K is the steady-state gain, τ is the dominant time constant, and L is the transport delay. In this study, the nominal parameters are

K=1.0

τ=10.0

L=1.5 s

For simulation and frequency-domain analysis, the time delay term e−Ls is approximated using a third-order Padé approximation, providing a rational transfer function representation suitable for MATLAB/Simulink and stability margin calculations. The resulting nominal plant model is then used as the baseline for controller tuning and robustness evaluation.

2.4 Model Parameters and Uncertainty Representation

To evaluate robustness under realistic variability, uncertainty is introduced in the key plant parameters K, τ, and L. A Monte Carlo approach is used to generate multiple plant variants by applying bounded uniform perturbations around the nominal values:

$K \in [K(1-0.30),\ K(1+0.30)]$ → ±30% gain uncertainty

$\tau \in [\tau(1-0.40),\ \tau(1+0.40)]$ → ±40% time-constant uncertainty

$L \in [L(1-0.20),\ L(1+0.20)]$ → ±20% delay uncertainty

A total of N = 50 random variants are evaluated. For each variant, closed-loop simulations are performed with the controller gains fixed, and stability is checked numerically. Performance is then quantified using time-domain metrics (rise time, settling time, overshoot, steady-state error), as well as actuator-related indicators such as peak control effort and saturation time. This uncertain structure allows robustness to be assessed without requiring detailed physical pump identification, while still testing controller sensitivity to the most influential dynamic parameters.

Control System Design

3.1 Control Objective

The control objective of this study is to control the pump system to maintain stable and efficient operation under parameter uncertainty and external disturbance. In practical industrial wastewater treatment plants, sudden inflow surges may arise from increased production demand, while human-related operational factors such as incorrect setpoint, delayed corrective action, or prolonged operation can further deviate the system from nominal conditions. Therefore, the controller is designed to control pump output while preserving stability and acceptable dynamic performance despite these combined sources of uncertainty and operational variability.

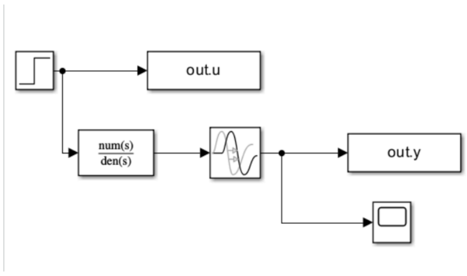

Figure 1

Closed-loop control architecture of the industrial pump system implemented in MATLAB/Simulink

3.2 Controller Selection

Initially, both PI and PID controllers were evaluated under nominal operating conditions to assess their baseline performance. The simulation results indicate that while the PID controller provided marginally improved transient performance compared to the PI controller, the overall difference in performance was not substantial. In particular, both controllers achieved comparable stability, steady-state accuracy, and disturbance rejection under nominal conditions.

Given the relatively small performance improvement offered by the PID controller and considering the increased complexity and sensitivity associated with derivative action, the PI controller was selected for subsequent analysis. This choice reflects the minimal performance difference observed and prioritizes simplicity, reliability, and ease of implementation, which are important considerations in industrial control applications.

3.3 PI Controller Design

The PI controller is defined by the following control law:

$$C_{PI}(s) = K_p + \frac{K_i}{s}$$

where Kp is the proportional gain and Ki is the integral gain. The proportional action increases response speed, while the integral action removes steady-state error caused by constant disturbances or model mismatch.

The PI gains were tuned on the **nominal FOPDT plant** (K=1.0, τ=10.0 s, L=1.5 s) to achieve stable tracking with acceptable overshoot and settling time. The final controller parameters used throughout all experiments are Kp=2.0 and Ki=0.4

These gains are fixed for all robustness tests (disturbance rejection, parameter uncertainty, and overload), so that any observed performance changes are related to plant variation and operating stress rather than controller retuning.

3.4 PID Controller Design

The PID controller is defined by the following control law:

$$C_{PID}(s) = K_p + \frac{K_i}{s} + K_d s$$

Kd denotes the derivative gain. The derivative term provides predictive action by responding to the rate of change of the system output, which can improve damping and reduce overshoot under nominal operating conditions (Franklin et al., 2015).

PID controller parameters was selected to enhance transient response while maintaining closed-loop stability. Compared to the PI controller, the PID controller is generally expected to offer improved rise time and reduced overshoot under nominal conditions. However, the inclusion of derivative action may also increase sensitivity to measurement noise and modeling uncertainty, which can negatively affect robustness in practical implementations (Ogata, 2010). For this reason, robustness evaluation of the PID controller is particularly important in the context of uncertain and degraded operating conditions.

3.5 Implementation in MATLAB/Simulink

Both PI and PID controllers were implemented within the MATLAB/Simulink system and connected to the nominal pump system model. The simulation system was used to model the closed-loop system behavior and evaluate controller performance under different operating conditions.

Controller performance was first evaluated under nominal operating conditions to verify closed-loop stability and baseline dynamic response. The same controller parameters were then retained for subsequent robustness analysis to ensure that observed performance variations under uncertainty, disturbances, and overload conditions were attributable to controller characteristics rather than controller retuning. This implementation approach reflects common industrial practice, where controllers are typically tuned for nominal operation and expected to maintain acceptable performance across a range of operating conditions (Åström & Hägglund, 2006).

3.6 Performance Metrics

To assess control performance, several time-domain metrics were considered, including rise time, settling time, overshoot, and steady-state error. These metrics provide quantitative measures of both transient and steady-state behavior and are widely used in industrial control system evaluation and comparative performance analysis (Franklin et al., 2015). The selected performance metrics form the basis for the comparative evaluation presented in the subsequent robustness analysis and results sections.

Robustness Analysis

4.1 Overview of Robustness Evaluation

Robustness analysis is conducted to evaluate the ability of the control system to maintain stability and acceptable performance under non-ideal operating conditions. In real industrial pump applications, operating conditions are rarely constant. Instead, pump systems are subjected to much parameter uncertainty, external disturbance, overload operation, and operational variability by fluctuating production demands and non-ideal operational practices.. These factors can significantly affect the system dynamics and may lead to degraded performance or instability if not properly addressed.

Robustness testing is performed with the controller fixed at Kp=2.0 and Ki=0.4. The nominal delay is approximated using a third-order Padé model to enable consistent frequency-domain stability analysis. Monte Carlo robustness uses N=50 random variants with bounded uncertainty K±30%, τ±40%, and L±20%. Disturbance rejection tests apply step disturbances after the system has reached steady state (measurement disturbance: +25% at t=60s, output/load disturbance: +25% at t=60s, input/actuator disturbance: +15% at t=100s).

In this study, robustness is evaluated through simulation-based testing using MATLAB/Simulink pump model. The controller parameters are fixed after nominal tuning and were not retuned for any robustness test. This approach reflects common industrial practice, where controllers are typically tuned for nominal operation and are expected to tolerate a range of operating variations without further adjustments. Performance is assessed using time-domain metrics such as rise time, settling time, overshoot, and steady-state error, which are widely used indicators of control system robustness and stability (Ogata, 2010; Åström & Murray, 2008).

4.2 Nominal Performance Baseline

As a baseline reference, the closed-loop pump system is first evaluated under nominal operating conditions. This baseline response provides expected system behavior under ideal situations and serves as a benchmark for comparison with the robustness tests.

Figure 2 presents the nominal closed-loop pump system to a step reference input. The system achieves a stable operation with satisfactory transient performance and a tolerable steady-state error. The response showed moderate overshoot followed by smooth convergence to the reference value, indicating sufficient damping and stability margins. This baseline performance confirms that the controller is properly tuned for nominal conditions and provides a valid reference point to evaluate performance degradation under non-ideal situations.

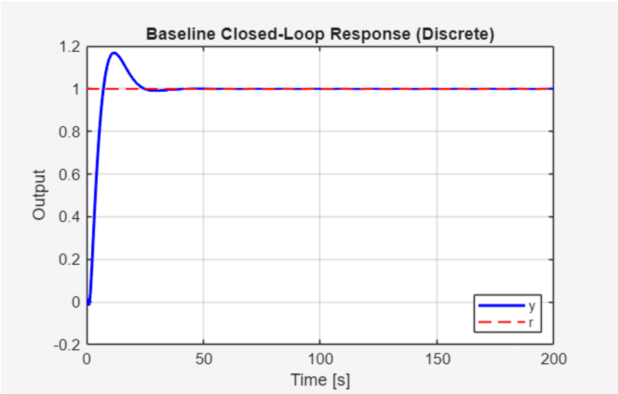

Figure 2

Nominal closed-loop response of the pump system under baseline operating conditions

4.3 Robustness to External Disturbance

Industrial pump systems are frequently exposed to external disturbances such as sudden inflow variations, load changes, and actuator-related perturbations. To evaluate disturbance rejection capability, three types of disturbances are introduced during steady-state operation: measurement disturbance, load disturbance, and actuator/input disturbance.

Figure 3 shows the closed-loop system response under these disturbance scenarios. In all situations, the disturbance is applied after the system has reached steady-state operation. The results indicate that the control system effectively reduces the impact of each disturbance and restores the output to the desired baseline value within a limited settling time. Although transient deviations are observed immediately following disturbance application, no sustained fluctuations or instability occur.

These results indicate that the controller possesses adequate disturbance rejection capability, which is a critical requirement for practical industrial control systems operating in uncertain environments (Franklin et al., 2015).

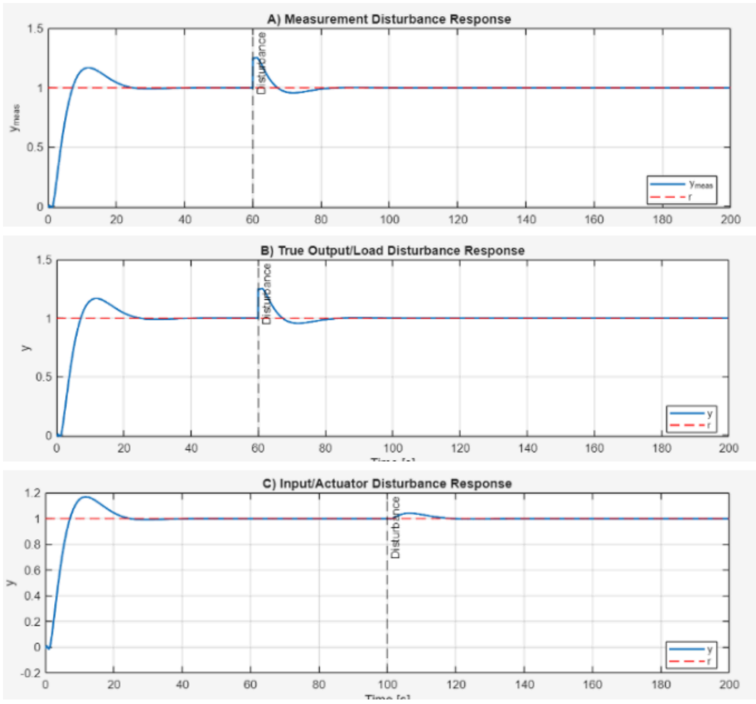

Figure 3

Closed-loop pump response under measurement, load, and actuator disturbance scenarios

4.4 Robustness to Parameter Uncertainty

In real-world applications, pump system parameters may vary due to aging, wear, changing fluid properties, or imperfect system identification. To assess resilience to this uncertainty, changes in critical model parameters are applied during simulation while keeping the controller gains unchanged.

Figure 4 displays the response of the closed-loop output and control effort across various stable plant designs resulting from parameter changes. The output trajectories remain limited and similar to the reference value for all tested cases, indicating maintained closed-loop stability. While variations in transient characteristics such as rise time and overshoot are observed, the overall system behavior remains acceptable. The corresponding control effort trajectories show moderate variation but remain within actuator limits.

These results demonstrate that the control system is robust to moderate parameter uncertainty and does not rely on precise model matching to maintain stability, which is a desirable property in industrial control applications (Skogestad & Postlethwaite, 2005).

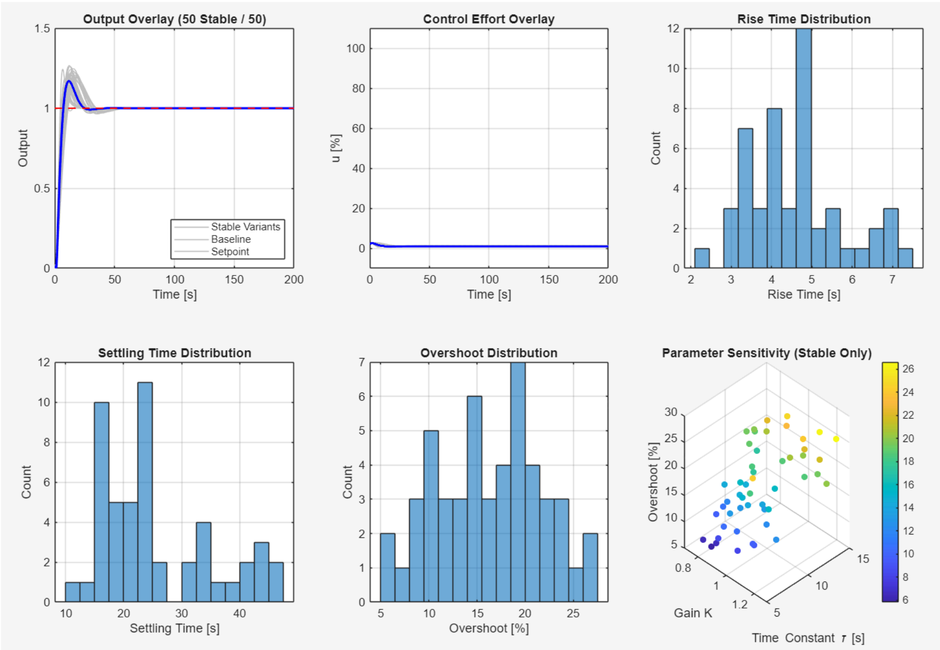

Figure 4.

Robustness analysis of the closed-loop pump control system under parameter uncertainty. The figure shows (a) output response overlay for multiple stable parameter variants, (b) control effort overlay, (c) rise time distribution, (d) settling time distribution, (e) overshoot distribution, and (f) parameter sensitivity of overshoot with reference to system gain and time constant.

4.5 Overload and Extended High-Demand Operation

Extended overload operation is simulated by increasing the setpoint from $r=1.0$ to $r=1.5$ during the interval $t=60$ s to $t=140$ s to represent sustained high demand. Simultaneously, degraded behavior are introduced to model stress-related performance loss using $K=0.70$, $\tau=1.60$, and $L=1.20$. Actuator saturation is enforced with $u\in[0,100]\%$, and an anti-windup correction is applied to prevent integrator windup during saturation.

Figure 5 shows the closed-loop output and corresponding control effort during extended overload operation. When the overload condition is applied, the system exhibits increased overshoot and longer settling time, reflecting the increased stress placed on the control loop. However, the system remains stable throughout the overload period and successfully recovers once nominal conditions are restored. The control effort remains limited and does not show constant saturation, indicating effective management of actuator constraints.

These observations indicate that the controller is capable of maintaining stability and acceptable performance under continuous high-demand operation, which is essential for real-world pump applications subject to unpredictable loading conditions.

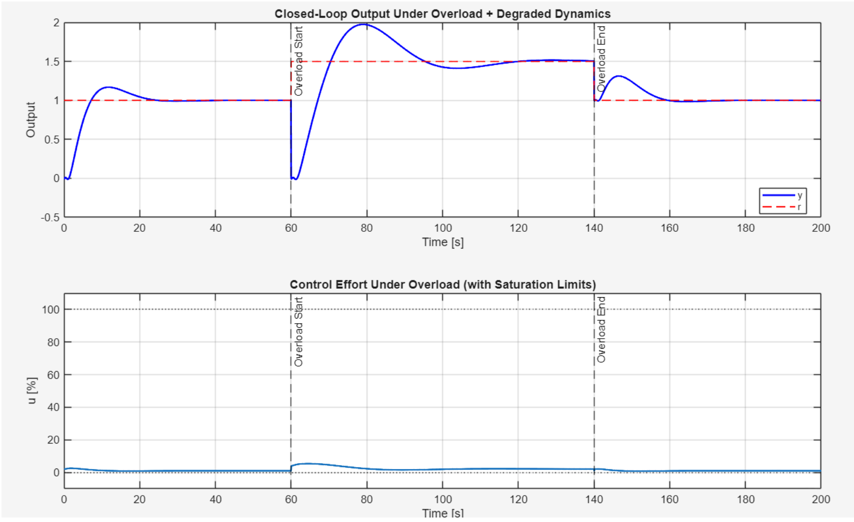

Figure 5

Pump system response under extended overload operation with degraded dynamics and actuator saturation limits.

4.6 Summary of Robustness Results

The robustness analysis proved that the designed control system maintains closed-loop stability and acceptable performance under a range of non-ideal operating conditions, including external disturbances, parameter uncertainty, and extended overload operation. While increased deviations and longer settling times are observed under severe conditions, the system consistently avoids instability and achieves steady-state tracking.

Disturbance rejection and parameter variation tests indicate that the controller does not rely on precise model matching to preserve stability, which is a valuable characteristic for industrial pump applications subject to aging, wear, and uncertain operating situations. Under extended overload conditions, the controller remains stable and recovers once nominal operation is restored, with control effort remaining within actuator limits.

It should be noted that sustained performance degradation or excessive fluctuation under prolonged overload conditions may reflect physical pump capacity limitations rather than insufficient controller design. In such cases, system-level modifications such as selecting a higher-capacity pump or three-phase pump may be required to ensure reliable operation under continuous high-demand conditions.

Conclusion

This study provided a simulation-based modeling and control system for evaluating the robustness of an industrial pump system operating under non-ideal conditions commonly encountered in wastewater treatment and industrial applications. A control-oriented dynamic model of the pump system was developed using MATLAB/Simulink, PI and PID controllers were designed and evaluated.

Nominal performance analysis demonstrated that both PI and PID controllers achieve stable closed-loop operation with comparable steady-state accuracy. Even though the PID controller provided marginal improvements in transient response, the PI controller was selected due to its simpler structure, robustness, and ease of usage, which are desirable characteristics in industrial environments.

Robustness analysis showed that the selected control strategy maintains stability and acceptable performance under external disturbances, parameter uncertainty, and extended overload operation. While performance degradation in terms of increased overshoot and settling time was observed under severe operating conditions, the system consistently minimized instability and recovered once nominal conditions were restored. These results confirm that the controller does not rely on precise modelling and is suitable for practical industrial pump applications subject to uncertainty and fluctuating demands.

Finally, the study highlights an important practical aspect to consider: robust control strategies can extend system performance within design limits but cannot overcome fundamental hardware limitations. Continuous fluctuations or degraded performance under constant overload conditions may indicate insufficient pump capacity rather than controller inefficiency, leading to operational solutions such as higher-capacity pumps or three-phase pump configurations. Overall, this work demonstrates the effectiveness of simulation-based robustness evaluation as a practical tool for control design and provides a foundation for future studies incorporating higher-order models, nonlinear effects, or experimental validation.

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