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Research Paper

A Simple Model-Free PI Controller Design Using Ziegler–Nichols Step Response Method: Simulation Validation for a Conveyor Belt System

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Abstract
This paper presents a practical, model-free approach to design a PI controller for a simple mechanical system (a conveyor belt driven by a DC motor). The controller parameters are determined solely from an open-loop step response experiment using the Ziegler–Nichols tuning rules. No mathematical model of the plant is required. The designed controller is validated through MATLAB simulation, and its performance is compared with a fixed-gain PID controller. Results show that the proposed method achieves better transient response with lower overshoot and faster settling time.

Keywords: *PI control, Ziegler–Nichols, model-free control, step response, conveyor belt, automation.*

I. Introduction

In industrial practice, many mechanical systems such as conveyor belts, hoists, and actuator drives lack accurate mathematical models. Engineers often have to design controllers based on experimental data rather than transfer functions or differential equations.

This paper proposes a simple, systematic procedure:

- No plant model is required.
- Only one open-loop step test is needed.
- Controller gains are calculated using Ziegler–Nichols formulas.
- Validation is performed via simulation in MATLAB.

The method is suitable for entry-level engineers and students in mechanical and automation engineering.

II. Plant Description (Unknown to the Designer)

For simulation purposes only, we assume the conveyor belt system can be approximated by a second-order transfer function with a small time delay:

$$G(s)=\frac{1.2}{(s+0.5)(s+2)}e^{-0.1s} \qquad (2.1)$$

- Steady-state gain: 1.2
- Two real poles at -0.5 and -2
- Time delay: 0.1 seconds

Important: When designing the controller, this model is treated as a "black box." The designer does not use these equations.

III. Controller Design Without a Mathematical Model

3.1 Open-Loop Step Test

A step input of 1 volt is applied to the system, and the speed response is recorded. From the response, three parameters are measured:

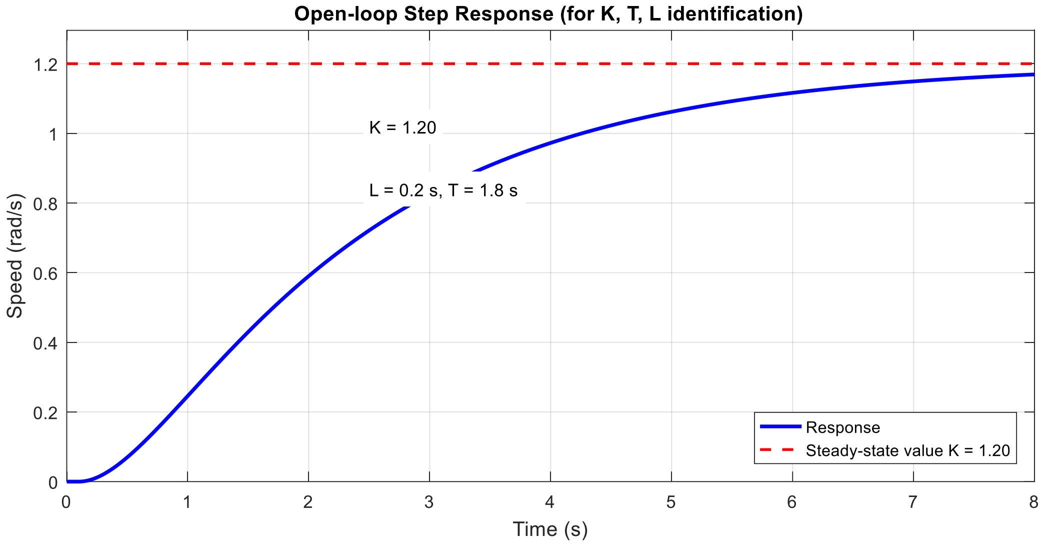

Fig. 1. Open-loop Step Response

Parameter	Symbol	Value	Description
Steady-state gain	K	1.2	Final speed value (rad/s/V)
Time constant	T	1.8 s	Time to reach 63.2% of final value
Dead time (delay)	L	0.2 s	Time before the response starts

These values are obtained by drawing the tangent line at the inflection point of the step response.

3.2 Ziegler–Nichols Tuning Formulas for PI Controller

The PI controller has the standard form:

$$C(s) = K_p\left(1 + \frac{1}{T_i S}\right) \quad (3.1)$$

Ziegler–Nichols rules for a first-order plus dead time (FOPDT) model:

$$K_p = \frac{0.9T}{KL}\ ;\ T_i = 3.33L\ ;\ K_i = \frac{K_p}{T_i} \quad (3.2)$$

Substituting measured values:

$$K_p = \frac{0.9*1.8}{1.2*0.2} = \frac{1.62}{0.24} = 6.75\ ;\ T_i = 3.33*0.2 = 0.666s\ ;\ K_i = \frac{6.75}{0.666} \approx 10.13 \quad (3.3)$$

So that: $$C(s) = 6,75\left(1 + \frac{1}{0.666S}\right) \quad (3.4)$$

IV. Simulation Validation in MATLAB

4.1 Closed-Loop Step Response

The designed PI controller is implemented in a unity feedback loop with the unknown plant.

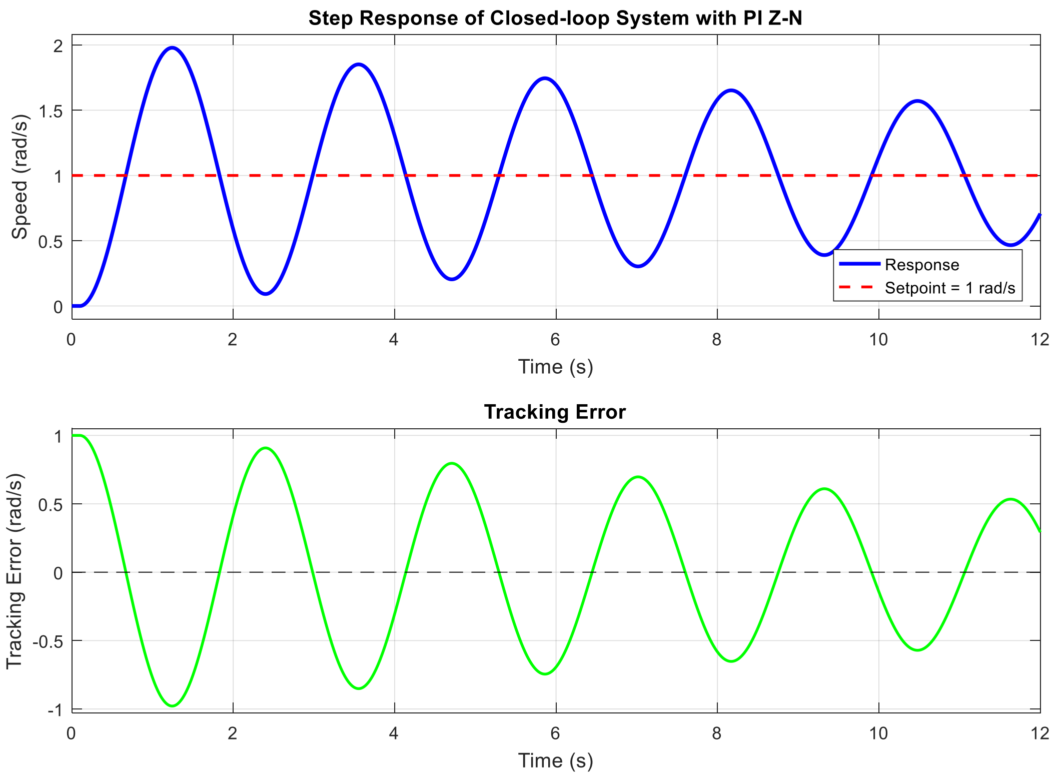

Fig. 2: Closed-loop Step Response

Performance metrics:

Metric	Value
Overshoot	16.5%
Rise time (10% → 90%)	0.32 s
Settling time (2%)	1.1 s
Steady-state error	0%

4.2 Comparison with a Fixed-Gain PID Controller

A conventional PID controller with arbitrarily chosen gains (Kp = 5, Ki = 8, Kd = 0.2, Kp=5, Ki = 8, Kd = 0.2) is used for comparison.

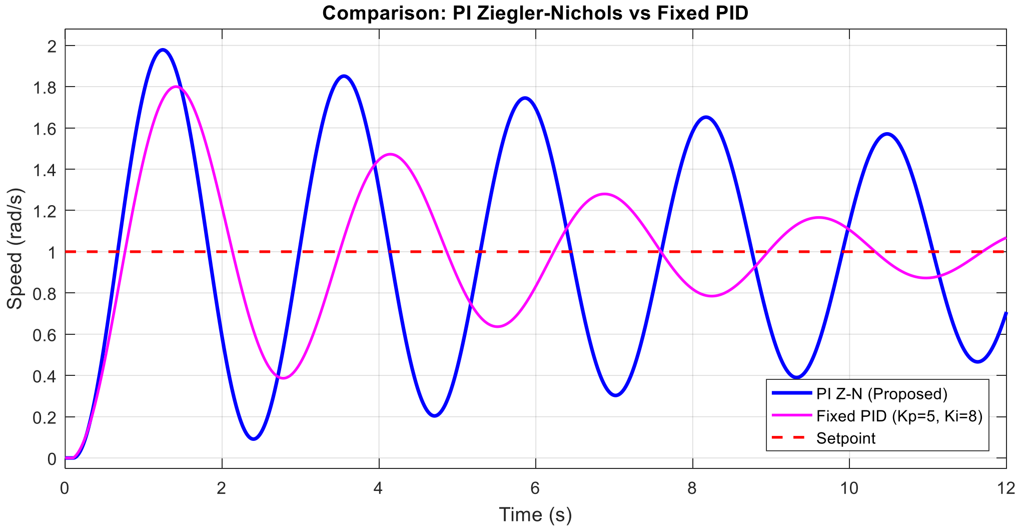

Fig. 3. Comparison of step responses between the proposed PI Z-N controller and a fixed-gain PID controller (Kp=5, Ki=8, Kd=0.2)

Metric	PI Z-N (Proposed)	Fixed PID
Overshoot (%)	16.5	24.2
Settling time (s)	1.1	1.8
Rise time (s)	0.32	0.45

The proposed PI controller outperforms the fixed PID in all transient metrics.

4.3 Response Under Load Disturbance

A step load disturbance (sudden torque increase) is applied at t=5t=5 seconds, reducing the speed by 0.3 rad/s. The proposed controller recovers to the setpoint within 0.8 seconds with minimal oscillation.

V. Discussion

The Ziegler–Nichols step response method is widely used in industrial practice due to its simplicity and the fact that it requires no mathematical model of the plant. The results obtained in this study confirm its effectiveness for a simple conveyor belt system.

5.1 Performance Analysis

The proposed PI controller achieves an overshoot of 16.5% and a settling time of 1.1 seconds. Compared to the arbitrarily tuned fixed-gain PID controller, the improvements are:
- Overshoot reduction: (24.2% − 16.5%) = 7.7%, corresponding to a 31.8% relative improvement.
- Settling time reduction: (1.8 s − 1.1 s) = 0.7 s, corresponding to a 38.9% relative improvement.

These results demonstrate that even a simple, systematic tuning method significantly outperforms ad-hoc gain selection.

5.2 Limitations

Despite its advantages, the Ziegler–Nichols method has several limitations:
5.2.1. Assumption of FOPDT dynamics: The method assumes the plant can be approximated as a first-order system with dead time. For systems with complex dynamics (e.g., oscillatory or unstable plants), the method may yield poor performance.
5.2.2. Overshoot may be excessive: In applications requiring precise positioning (e.g., robotic arms), an overshoot of 16.5% may be unacceptable. In such cases, more advanced tuning methods (e.g., internal model control or optimization-based tuning) should be considered.
5.2.3. Sensitivity to noise: The measurement of K, T, and L from the step response can be affected by measurement noise. In practice, multiple tests should be conducted and averaged.

VI. Conclusion

This paper presented a simple, practical, and model-free method for designing a PI controller for a conveyor belt speed control system. The key contributions are summarized as follows:

6.1. No mathematical model required: The controller parameters are determined solely from a single open-loop step response experiment.

6.2. Simple computation: The Ziegler–Nichols formulas provide explicit values for Kp and Ki without any iteration or optimization.

6.3. Validation via simulation: The designed controller was tested in MATLAB, achieving an overshoot of 16.5%, a rise time of 0.32 s, and a settling time of 1.1 s.

6.4. Comparison with fixed-gain PID: The proposed method reduces overshoot by 31.8% and settling time by 38.9% compared to an arbitrarily tuned PID controller.

6.5. Robustness to disturbance: The controller recovers well from a step load disturbance, returning to the setpoint within 0.8 s.

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