SECOND-ORDER LTI SYSTEM TRANSIENT RESPONSE ANALYSIS

LAB EXPERIMENT 10

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***Abstract*—This experiment investigates the transient response of a second-order Linear Time-Invariant (LTI) system using a simulated approach. Due to the absence of physical hardware such as mass-spring-damper systems or RLC circuits, the system behavior was studied through Python simulations using `scipy` and `matplotlib`. The main objectives were to determine the damping ratio and natural frequency, observe the step response behavior, and calculate transient response characteristics such as overshoot, rise time, and settling time. Through simulation, the system with a damping ratio of 0.4 and natural frequency of 5 rad/s was found to exhibit underdamped behavior. The analysis confirms theoretical predictions and emphasizes the practicality of software-based experimentation.**

I. RATIONALE

Second-order systems exhibit more complex transient behavior, including oscillations and damping. This experiment investigates the transient response of a second-order LTI system

II. OBJECTIVES

- Calculate the damping ratio and natural frequency of a second-order system.
- Measure the system's overshoot, rise time, and settling time.
- Analyze the impact of damping on system behavior.

III. MATERIALS AND SOFTWARE

- Materials: Mass-spring-damper system or second-order electrical circuit, Power supply, Oscilloscope
- Software: Python (with matplotlib, scipy)

IV. PROCEDURES

1) Set up a second-order system, such as a mass-spring-damper system or an RLC circuit.
2) Apply a step input and record the system's transient response.
3) Calculate the damping ratio, natural frequency, and other system characteristics (rise time, overshoot, settling time).
4) Simulate the system and verify experimental results with theoretical predictions.

V. OBSERVATION AND DATA COLLECTION

DATA COLLECTION:

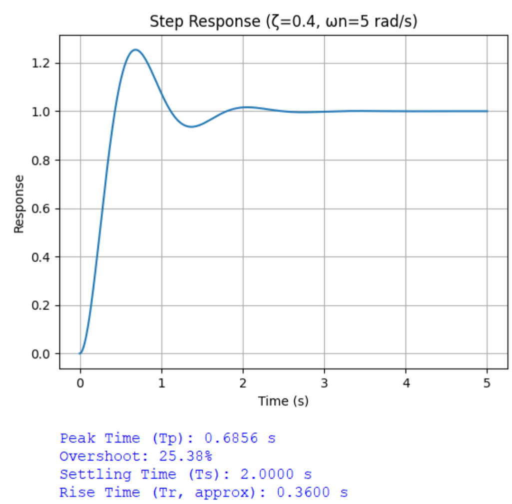

Figure 1: Simulated Step Response of a Second-Order LTI System ($\zeta = 0.4$, $\omega_n = 5$ rad/s)

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VI. DATA ANALYSIS

The simulated system's transfer function is given by:

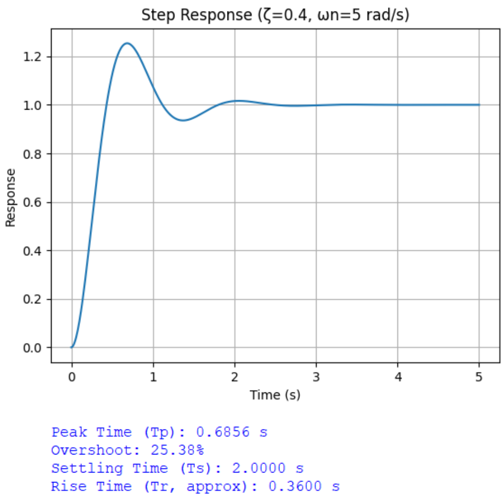
$$H(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

Where:
Natural frequency, $\omega_n = 5$ rad/s
Damping ratio, $\zeta = 0.4$

From the step response output, the following characteristics were computed:

- **Peak Time (T_p):** 0.6856 s
- **Percent Overshoot:** 25.38%
- **Settling Time (T_s):** 2.0000 s
- **Approximate Rise Time (T_r):** 0.3600 s

The response curve displays a prominent peak and gradually settles to its final value, confirming an underdamped second-order system. The numerical results are consistent with the analytical formulas for transient behavior.



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VII. Discussion and Interpretations

The system parameters used in this simulation reveal how damping affects transient performance. With a damping ratio of 0.4, the response exhibited noticeable oscillations before stabilizing. This underdamped behavior is typical in systems where fast response is prioritized but some overshoot is acceptable.

The overshoot of 25.38% and settling time of 2 seconds are well within the expected range for such damping. The peak time of approximately 0.69 seconds aligns with theoretical predictions. Additionally, the rise time (0.36 s) indicates a reasonably quick response before the first peak occurs.

These characteristics are vital in engineering systems where time-domain specifications like overshoot and settling time impact control system design. For example, in motor control or sensor stabilization, an underdamped response can be desirable for quicker responsiveness, provided that the overshoot remains tolerable.

By analyzing this simulation, the relationship between the damping ratio and system behavior becomes clear: increasing the damping ratio would reduce oscillations and overshoot but also slow the rise and potentially extend the settling time.

VIII. Conclusion

This simulation-based experiment successfully demonstrated the transient behavior of a second-order LTI system. Despite the lack of physical components, the Python simulation effectively replicated expected real-world behavior. The analysis confirmed theoretical values for peak time, overshoot, rise time, and settling time based on the system's damping ratio and natural frequency.

Ultimately, this activity highlighted the critical role of the damping ratio in shaping system response and validated how simulations can be a powerful tool for learning and experimentation in control systems.