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Original Article

Analysis of System Stability using Bode and Nyquist Criteria for Recycling Used Engine Oil in KSA

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Abstract - *Reusing used engine oil is essential for resource conservation and environmental sustainability. Control systems are critical to the operations of these recycling systems. Via the application of chemical treatment and control systems engineering, the current research plugs an important gap in the literature. It focuses on investigating the responsiveness and stability of a PID-controlled system utilized in the acid-based recycling of used motor oil. By regulating the yield and maintaining the qualities and specifications near the base oil specification during the experiment, the treatment process was carried out at a constant 45°C. This paper focuses on applying a control scheme to manage the acidic strategy of recycling used engine oil. Meanwhile, we monitored and adjusted the oil density, viscosity, and temperature. Simulink was used to construct the experiment. MATLAB software's toolbox was utilized to estimate the transfer function for recycling old engine oil through system identification using a graphical user interface approach. The stability analysis was examined using the Bode and Nyquist diagrams. The results showed that the gain margin is predicted to be 29.8 dB at a phase of 180 ° using the Bode diagram. The system's max gain is assessed to be 14.7dB, which provides insight into the system's tendency to overshoot in the time domain response. In addition to estimation, the peak gain and gain margin were established as the minimum, and all stability regions were explored using a Bode diagram. Furthermore, the analysis was performed using the Nyquist diagram, and the findings revealed a phase margin of 166 degrees and a peak gain of 14.7 dB. In conclusion, control system analysis utilizing Bode plots and Nyquist diagrams is critical for optimizing the recycling process of used engine oil.*

Keywords - *Stability, Frequency, Acidic, Transfer function, Bode plot, Nyquist criterion identification, Control system.*

1. Introduction

Under the severity of the environmental situation, a single gallon of old oil could contaminate up to 1 million gallons of clean water. (R. 2024). Recycled motor oil was made from engine oil (15W-40) using an activated carbon adsorbent along with a mix of MEK and 1-butanol solvents. Response Surface Methodology (RSM) was used to improve the recycled engine oil, and the Box-Behnken Design (BBD) within RSM helped create the experimental design. Response Surface Methodology (RSM) is used to optimize recycled engine oil, and the Box-Behnken Design (BBD) package within RSM was used to build the experimental design matrix. (Negasa Abdena Alemu 2025).

(Rao 2022), explained that a control system is a collection of components that work together to achieve a control goal. The controller receives data from the measuring devices and, after calculation, decides what action to take. The final control element manipulates a process variable. A single-loop feedback control setup is a fundamental control approach. A single-loop feedback control system consists of two paths: feedforward and feedback. Computer simulation is extremely useful in the analysis and design of control systems.

It is also a useful, low-cost tool for process control teaching. Simulation studies allow engineering students to develop a thorough understanding of theoretical topics, solve educational difficulties, and gain practical experience. (Silva, 2023), the suggested control system requires at least one controller. PID and PI controllers are among the most widely utilized in industry.

The control software is located next to the controllers. Scilab is an excellent example of control software. It is described as free code software with no cost for purchase, as well as a high computational capacity and integrated modeling and simulation tools.

(Rao 2022), stated that engineers need an objective way to assess the performance of the control schemes they consider when constructing process control systems. Quantitative measurements of the system's reaction to a particular input or test signal are called performance criteria.

Chen (2003) proposed the stability method of decentralized PI control systems using Nyquist stability analysis. A stability region has been determined for each PI controller using system frequency response information. A tuning strategy is given based on the acquired stability region and a new column diagonal dominance index for each loop. The resulting decentralized control mechanism ensures closed-loop stability.The simulation results show that this design strategy performs well for a wide range of scenarios.

(Åström 2021), concluded that the Bode graphic provides a brief summary of a system. Many attributes can be extracted from the plot, and because logarithmic scales are utilized, the plot provides properties over a wide range of frequencies. Because any signal can be converted into a sum of sinusoids, it is possible to visualize a system's activity over a wide frequency range. Furthermore, when the gain curves approach the asymptotes, the system can be modeled using integrators or differentiators.

(Aldemir, 2020) This study used RSM to determine the optimal PID controller parameters to minimize the ISE and IAE performance criteria after applying the three most extensively used tuning methods to the experimental liquid level system. Dynamic analysis was performed on the liquid level control system to generate the reaction curve, and the dead time, time constant, and process gain values were calculated. PID control parameters were computed using typical tuning methods such as Cohen-Coon, Ziegler-Nichols, and Yuwana-Seborg.

(Goud 2022), this research proposed a temperature adjustment in response to the abrupt change in flow rate and temperature. The controller needs to be precisely set to keep the reactor's response temperature at the reference value. The PID controller parameters are calculated using a unique approach that uses the swarm algorithm. (Juneja (2021) stated that the classical PID controllers have numerous drawbacks. One of them is the difficulty in dealing with disturbance, dead time, and restrictions while using PID controllers. To address all of the issues associated with traditional controllers, control systems based on soft computing approaches are developed. Some examples of soft computing techniques include GA, FLC, and ANN.

(Das (2023)) Taking into account the challenges of controlling a constantly stirred tank reactor, heat exchangers, boiler steam drum, and distillation column, an improved dual degree of freedom controller architecture is provided. The internal loop employs a proportional-derivative controller with defined gain and phase margin. The external proportional-integral controller is redesigned using the moment matching method.

(Tsavnin, 2020) This work described a strategy for PID-controller tuning that provides a non-overshoot step response for a second-order transfer function with interval-defined parameters. Furthermore, stability is an important performance metric in many control applications.

(Mahmud 2020), compared the performance of PID, PI, and fuzzy logic controllers. The results show that the PID controller provides the best performance compared to the other two controllers, PI and fuzzy logic. The design was validated using a MATLAB simulation. (Ahmed, 2020), illustrated that PID controllers are more accurate than FL controllers, despite the rigorous mathematical modeling required for their design. The paper contributes to using a GUI to estimate the transfer function for a recycled engine and to conduct stability studies using the Bode and Nyquist diagrams. Despite Bode and Nyquist tests being widely used in conventional process industries to evaluate the stability of control systems, their use in recycling used engine oil is still mainly unexplored. This causes a significant gap.

2. Experimental Data

2.1. Experimental Approach

The chemical engineering lab at Jazan University carried out the experiments with the help of samples of engine oil used at car stations in Jazan City. The old oil was from vehicles that had driven for 5000 km, and this measured its density and viscosity. The density was 0.91 g/ml, and the viscosity was 30 cp. After filtering and treating with formic acid and acetic acid, the process was done at 45°C. The density and viscosity of the new oil were 0.86 and 30 when using formic acid and 0.87 g/ml and 28 cp when using acetic acid, as shown in Table 1.

Table 1. Shows the experimental results for the viscosity and density of the treated oil with acetic and formic acid. Experimental

Oil type	Density (g/ml)	Viscosity (cp)
Fresh oil	0.87	30
Used engine oil	0.91	16
Treated oil with formic acid	0.8614	30
Treated oil with acetic acid	0.87	28

3. Mathematical Model

3.1. PID Model

(Goodwin 2001)The following mathematical equation describes a proportional-integral-derivative (PID) controller:

$$U(s) = Kp\ E(s) + Ki\frac{E(s)}{s} + Kd\ E(s) \quad (1)$$

Where:

- U(s) is the control output,
- E(s) is the error signal, defined as the difference between the desired set point and the measured process variable:
- Kp is the proportional gain,
- Ki is the integral gain,

- Kd is the derivative gain,
- S is the complex frequency variable in the Laplace transform.

3.2. Bode Model

The Bode plot depicts the frequency response of a system. It has two plots: the magnitude plot and the phase plot. (Goodwin 2001)

Magnitude Plot: Displays the magnitude (gain) of the system's transfer function as a function of frequency (decibels, dB).

$$\text{Magnitude (dB)} = 20\log10\ |H(j\ \omega)| \quad (2)$$

Phase Plot: Displays the phase angle of the system's transfer function in frequency (in degrees).

$$\text{Phase (degrees)} = \arg(H(j\ \omega)).\ (180\backslash pi) \quad (3)$$

Where H (j ω) is the system's transfer function evaluated at s = j ω, where ω is the angular frequency in radians per second.

3.3. Nyquist Model

The Nyquist plot visualizes a system's frequency response by showing the real and imaginary components of the transfer function as a parametric plot, with frequency as the parameter. (Goodwin 2001)

Nyquist Plot: Plots H (j ω) in the complex plane as ω varies from (- ∞ to + ∞).

The transfer function (H(s)) is given by:

$$H(s) = N(s)\ /\ D(s) \quad (4)$$

Where N(s) and D(s) are the numerator and denominator polynomials of the transfer function, respectively.

Both plots provide insight into the stability and frequency response of control systems.

3.4. Transfer Function Estimation Model

The GUI estimated the transfer function after temperature and viscosity data were imported into the system. The transfer function is:

$$Gs = \frac{Y}{U} = \frac{0.1748\ S+0.03174}{S\string^3+0.1773S\string^2+0.45S+0.057} \quad (5)$$

4. Results

The control system was developed using the MATLAB program and Simulink to establish the control loop with the presence of a PID controller, as shown in Figure 1, to control and analyze the product requirements while comparing them to base oil.

As shown in Figure 2, the step response of a control system revealed a final value of 0.554, and by examining these parameters, engineers may analyze and develop control systems to satisfy desired performance standards while maintaining stability.

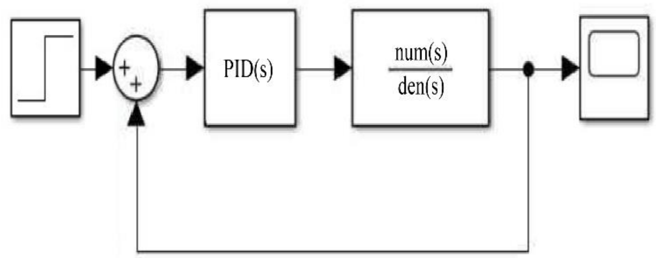

Fig. 1 The block diagram for the control system loop using Simulink

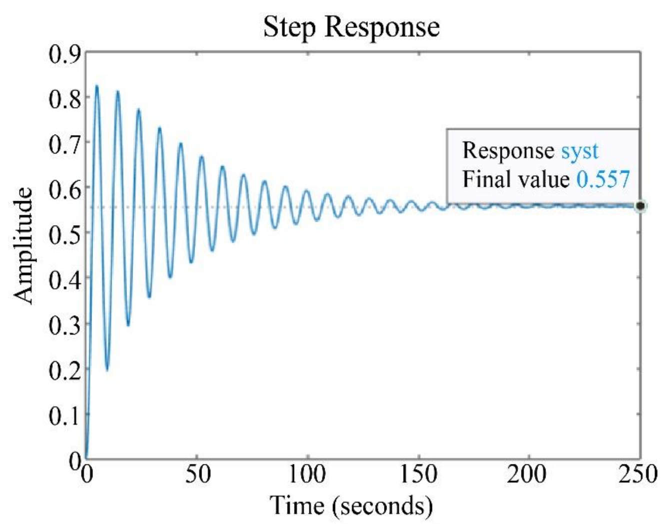

Fig. 2 Shows the response curve for a step response

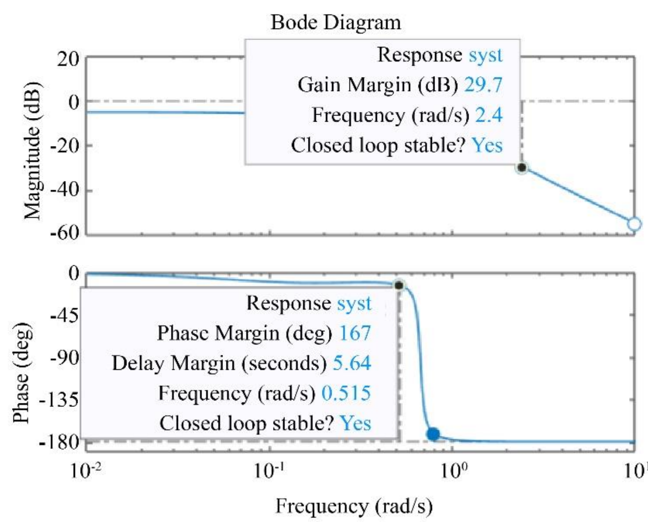

Fig. 3 Shows the minimum stability margin using a Bode plot

The gain margin is determined when the phase is -180 degrees. The predicted value is 29.8 dB when the Bode diagram is employed as shown in Figure 3. The positive value of the magnitude value indicates the system is stable.

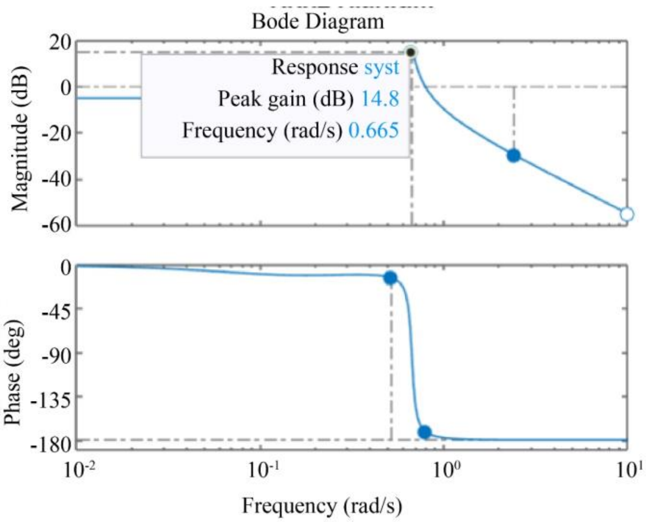

Fig. 4 Shows the peak gain using a Bode diagram

The system's peak gain is assessed to be 14.7 dB, which provides insights into the system's tendency for overshoot in the time domain response.

Figure 5 shows that the phase margin is 166 (degrees) using the Nyquist diagram (where the Nyquist plot intersects the unit circle) and measuring the angle between this point and the negative real axis.

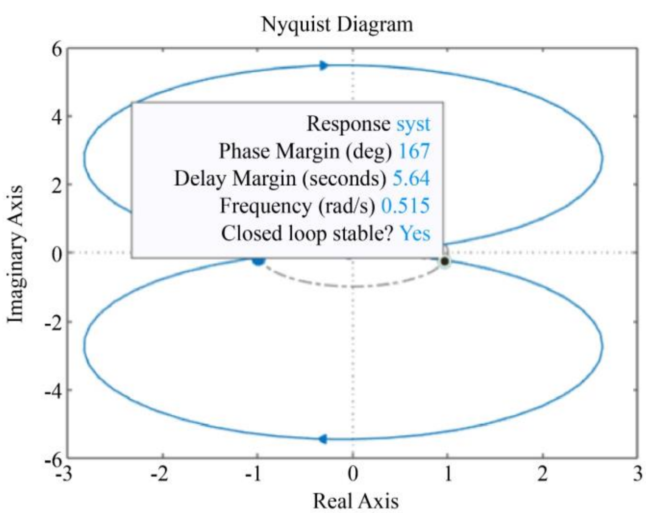

Fig. 5 Shows the phase margin using the Nyquist diagram

Figure 6 displays a peak gain of 14.7 dB, also known as the resonant peak, which displays the maximum value of the system's frequency. The most important parameters of the Bode plot and Nyquist diagrams are shown in the table below.

Table 2. Shows the phase margin and peak gain for the Bode plot and Nyquist diagram

Method	Phase Margin	Peak gain
Bode	180 °	14.7dB
nyquist	166°	14.7dB

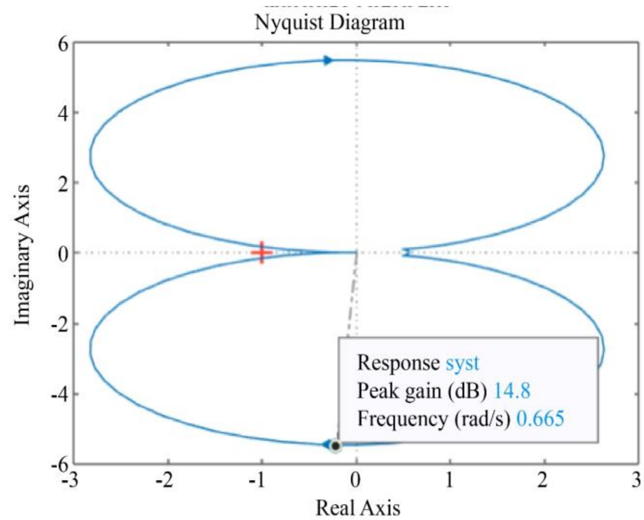

Fig. 6 Shows the peak gain response using the Nyquist diagram

On the other hand, a Bode plot yields a phase margin of 166°, but the Nyquist diagram used in this paper yields 180°. In the meantime, such results are satisfactory when compared to the literature, where the Phase Margin (PM) and Gain Margin (GM) were properly adjusted to exceed the minimal stability requirements identified in previous research (usually GM > 6 dB, PM > 45°).

5. Conclusion

- This paper highlighted the essentials of using Bode plots and Nyquist diagrams to optimize the control system's frequency response and stability characteristics in recycling spent engine oil.
- The paper analyzed the step response of a control system's properties, such as rise time, peak time, maximum overshoot, and settling time.
- This paper estimated the gain margin for a phase of 180°. When using the Bode diagram, the anticipated value is 29.8 dB. The positive value of the magnitude value suggested that the system is stable.
- The paper focuses on the estimation of the peak gain in a Bode diagram, also known as the resonant peak or maximum magnitude, which is the maximum value of the system's magnitude response across the frequency range. This peak gain can provide information about the system's resonant behavior and the possibility of overshoot in the time domain response.
- More study on system stability is recommended, as well as a deeper investigation of all techniques of recycling old engine oil.

5.1. Recommendations

Despite careful consideration, constraints may appear:

- While models usually assume linear time-invariant systems, the actual recycling process may not be linear due to temperature degradation and different oil characteristics. Furthermore, recycling used engine oil is an ethical issue with regard to industry and society's responsibilities.
- Oil tests conducted at high temperatures could reveal a risk of fire or hazardous gases.
- To adhere to ethical standards, individuals, companies, and governments have to manage waste oil in an efficient manner that has no adverse effect on the ecosystem.

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