EEE 480: Feedback Systems
Laboratory Assignment # 7

Design and Analysis of a Speed (Cruise) Control System for a Sikorsky UH-60A Blackhawk Helicopter

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1 Introduction

In this laboratory assignment, we will design and analyze a speed control system for a Sikorsky UH-60A Blackhawk Combat Assault Helicopter. Please answer all of the questions in each section, and include all of your plots in your report. MATLAB version 5.0 (or higher) will be used in this lab.

It should be noted that the questions which are asked below are questions which any control system engineer should ask - regardless of the physical system which they are considering. In this sense, they are standard questions.

2 Sikorsky UH-60A Blackhawk Longitudinal Dynamics

In this section, you will analyze the longitudinal (fore-aft-pitching) dynamics for a Sikorsky UH-60A Blackhawk. For simplicity, we consider a simplified linear model which is valid near hover. The helicopter input (i.e. control) is called the *cyclic pitch control* and is denoted by the symbol B_{l_c}. This control is used to control the effective "tilt" of the helicopter's main rotor. This indirectly controls pitching moments about the helicopter's center of gravity, the pitch attitude, and the helicopter's speed.

The transfer function from the cyclic control ($u = B_{lc}$, measured in *radians*) to the forward horizontal speed ($\dot{x}$, measured in ft/sec) is:

$$P(s) = \frac{\dot{x}}{B_{l_c}} = \frac{27.4s^2 + 84.94s + 1525}{s^3 + 3.16s^2 + 0.186s + 1.324}. \tag{1}$$

This transfer function will be referred to as the *plant transfer function.* It will be used as the basis for your cruise control system design.

1. What are the plant poles? Discuss the physical significance of each mode.
2. Is this system stable or unstable? Why?
3. What are the plant zeros? Discuss their physical significance. Hint: Think in terms of sinusoidal inputs.

4. Plot the plant's frequency response. Hint: Use the *bode* command in MATLB. Explain the nature of the peak on plant magnitude plot. Why is the peak present? Which poles are responsible for the peak?

3 Speed (Cruise) Control System Design and Analysis

In this section, you will design a speed (cruise) control system for the Blackhawk. Your control system design will be based on the block diagram shown in Figure 1. The series compensator, K, and the command pre-filter, W, are assumed to possess the following structure:

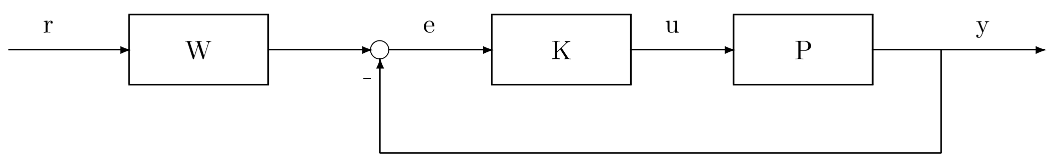

Figure 1: Visualization of Speed (Cruise) Control System To Be Designed

$$K(s) = k\left[\frac{s+a}{s}\right]\left[\frac{s+b}{b}\right]^2\left[\frac{50}{s+50}\right]^3 \quad (2)$$

$$W(s) = \left[\frac{b}{s+b}\right]^2 \quad (3)$$

1. Select the design parameters (i.e. a, b, and k) such that the closed-loop system satisfies the following closed loop design specifications, for a speed step command of 88 ft/sec (roughly 60 mph):

   - $\dot{x}(10sec) \approx 82\ ft/sec$;
   - $u(10sec) \approx 0.069\ rad\ (4\ deg)$;
   - $\theta_{min} \approx \theta(2.1sec) \approx 32\ deg$.

   To do this, it is necessary to be able to plot the pitch attitude of the helicopter. The transfer function from the control $u = B_{l_c}$ (measured in radians) to the pitch attitude θ (measured in radians) is given by:

   $$\frac{\theta}{B_{lc}} = \frac{-47.24s - 1.711}{s^3 + 3.16s^2 + 0.186s + 1.324}. \quad (4)$$

   Explain the structure selecterd for K and W.

2. What are the poles and zeros of your designed compensator K?

3. Plot the frequency response of your compensator, K.

4. Discuss the step command following and step output disturbance rejection capabilities of your design. Your discussion should relate to the frequency response plotted above.

5. Use MATLAB to form the open loop system

$$L(s) = P(s)K(s). \tag{5}$$

   Make sure you have done this correctly by verifying the open loop poles and zeros.

6. Use MATLAB to construct a root locus for your design. Hint: Use the *rlocus* command in MATLAB. Use classical root locus rules to discuss the generated plot.

7. What are the imaginary crossovers on the root locus? Hint: Use the *rlocfind* command in MATLAB.

8. Use MATLAB to plot the open loop frequency response.

9. What is the phase crossover frequency ω_{p_1} associated with your design; i.e. at what frequency ω_{p_1} is

$$\angle L(j\omega_{p_1}) = -180 \pm 360m \; deg? \tag{6}$$

10. Use MATLAB to compute $k_1 = \frac{1}{|L(j\omega_{p_1})|}$. What is the significance of k_1 and ω_{p_1} on the root locus plotted above?

11. What is the *unity gain crossover frequency* associated with your design; i.e. the lowest frequency, ω_g, such that

$$|L(j\omega_g)| = 1(0db)? \tag{7}$$

12. What is the *phase margin PM* associated with your control system design? Recall that

$$PM \stackrel{\text{def}}{=} 180 + \angle L(j\omega_g) \text{ deg}. \tag{8}$$

    What is the significance of the phase margin?

13. What is the downward gain margin, $\downarrow GM$? What is its physical significance?

14. What is the upward gain margin, $\uparrow GM$? What is its physical significance?

15. What information does the *margin* command in MATLAB provide? How do the results of the *margin* command relate to what you have computed above?

16. How would the upward gain margin, $\uparrow GM$, associated with your design change if K was given by

$$K(s) = k\left[\frac{s+a}{s}\right]\left[\frac{s+b}{b}\right]^2\left[\frac{50}{s+50}\right]^4 \tag{9}$$

    instead?

17. Plot the sensitivity frequency response. Recall that

$$S \stackrel{\text{def}}{=} \frac{1}{1+PK} \tag{10}$$

18. Over what frequency range is $|S(j\omega)| \leq 0.1$ (-20 db)?

19. What is the transfer function from r to the tracking error,

$$e_t \stackrel{\text{def}}{=} r - y? \tag{11}$$

    Please note that it is not S.

20. Why doesn't the sensitivity directly tell us about low frequency command following? Hint: Do not forget the definition of the tracking error and the effect of the pre-filter W.

21. Plot the complementary sensitivity fequency response. Recall that

$$T(s) \stackrel{\text{def}}{=} 1 - S(s). \tag{12}$$

22. Use MATLAB to form the transfer function from r to y. Plot the frequency response associated with this transfer function.

23. What is the approximate steady state output when the speed reference command is $r(t) = \sin 2t$? Hint: You can read this right off of the bode plot.

24. Plot the frequency response for the transfer function from r to the tracking error, e_t (computed above).

25. Suppose that a reference speed command $r(t) = A\ \sin(\omega t + \theta)$ is issued to the control system. For what ω values will the steady state tracking error $e_{t_{ss}}$ satisfy: $|e_{t_{ss}}| < 0.1\ A$?

26. What is the approximate steady state tracking error, $e_{t_{ss}}$, when a reference command $r(t) = \sin t$ is issued to the control system. Is your control system design intended to operate with a reference command r of this frequency? Explain.

27. What is the transfer function from r to the control, u? Plot the frequency response for this transfer function. Discuss how reference commands are attenuated in producing the control.