Indian Institute of Technology Hyderabad
Department of Electrical Engineering
EE2220 – Control Systems

भारतीय प्रौद्योगिकी संस्थान हैदराबाद
Indian Institute of Technology Hyderabad

Assignment 04 – (Design in Frequency Domain 2)
Submission Deadline: None

Key Learning from the Assignment:

- Designing PD, PI and PID controllers
- Designing controllers for systems
- Case study from hybrid electric vehicle example

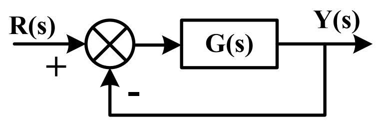
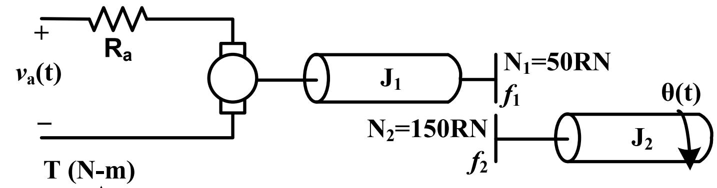


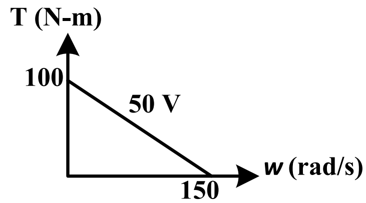
Figure 1

Instructions: RN = last two digits of your roll number.
Use Graph paper for all plots/ sketches.

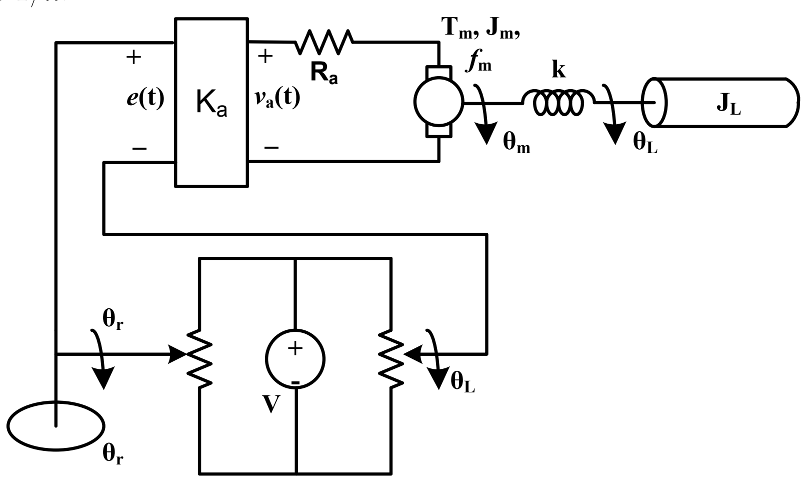
1. For a unity feedback system shown in Fig. 1, $G(s)=\dfrac{K}{s(s+1)}$. Design a PD controller such that the phase margin of the system is 45° and appropriate steady state error is less than or equal to 1/15 units of the final output value. Further the gain crossover frequency of the system must be less than 7.5 rad/sec.
2. Given the unity feedback system of Fig. 1, with $G(s)=\dfrac{K(s+10)(s+11)}{s(s+3)(s+6)(s+9)}$. Use frequency response method to design a PI controller to yield zero steady state error for parabolic input and peak overshoot of 15%.
3. For a unity feedback system shown in Fig. 1, $G(s)=\dfrac{K}{s(s+2)(s+4)(s+6)}$.
    a. Design a PD controller to yield a $K_v = 2$ and a phase margin of 30°.
    b. Design a PI controller to yield a $K_v = \infty$ and a phase margin of 30°.
    c. Design a PID controller to yield a $K_v = \infty$ and a phase margin of 30°.
    d. Use MATLAB/SCILAB to validate if your design in (a), (b) and (c) yields required phase margin or not. If your design is not satisfactory, redo the design using software of your choice.
    e. Compare performance of compensators designed in (a), (b) and (c) in terms of the following: bandwidth, peak time, maximum peak-overshoot, settling time. Use software of your choice.
4. A position control system is to be designed such that maximum peak overshoot is less than 25%. Further, appropriate error constant should be 50. For the motor to be used, load and torque speed curve is shown below, where, J_1 = 2 kg-m^2, J_2 = 18 kg-m^2, f_1 = 2 N-m-s/rad, f_2 = 36 N-m-s/rad. (Although obvious, consider position as the controlled variable and armature voltage as the manipulated variable.).
    a. Design a lead compensator for the system.
    b. Check performance of the controller using MATLAB/SCILAB.
    c. Design a lag compensator for the system.

d. Compare performance of the controllers designed in (a) and (c).





5. A position control system is shown in the figure below. The proportional controller used presently (K_a) is not providing satisfactory performance. Design appropriate controller to achieve maximum peak overshoot less than 15%. Further, the load should be positioned with 1% accuracy. For the motor to be used, load and torque-speed curve is shown above. System parameters are: J_m = 2 kg-m^2, J_L = 10 kg-m^2, f_m = 2 N-m-s/rad, k = 12 N-m/rad, sensitivity of error detector is $1/\pi$.



CASE Study Problem:

The use of hybrid cars is becoming increasingly popular. A hybrid electric vehicle (HEV) combines electric machine(s) with an internal combustion engine (ICE), making it possible (along with other fuel consumption-reducing measures, such as stopping the ICE at traffic lights) to use smaller and more efficient gasoline engines. Thus, the efficiency advantages of the electric drivetrain are obtained, while the energy needed to power the electric motor is stored in the onboard fuel tank and not in a large and heavy battery pack.

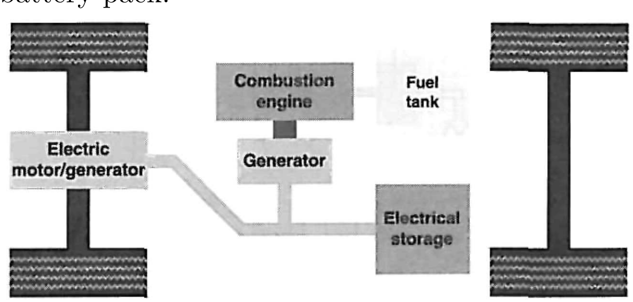


Fig. 1: Series HEV

There are various ways to arrange the flow of power in hybrid car. In a serial HEV (shown in Fig. 1), the ICE is not connected to the drive shaft. It drives only the generator, which charges the batteries and/ or supplies power to the electric motor(s) through an inverter or a converter.

The HEVs sold today are primarily of the parallel or split-power variety. If the combustion engine can turn the drive wheels as well as the generator, then the vehicle is referred to as a parallel hybrid, because both an electric motor and the ICE can drive the vehicle. A parallel hybrid car (Fig. 2) includes a relatively small battery pack (electrical storage) to put out extra power to the electric motor when fast acceleration is needed. See (Bosch 5th ed., 2000), (Bosch 7th ed., 2007), (Edelson, 2008), (Anderson, 2009) for more detailed information about HEV.

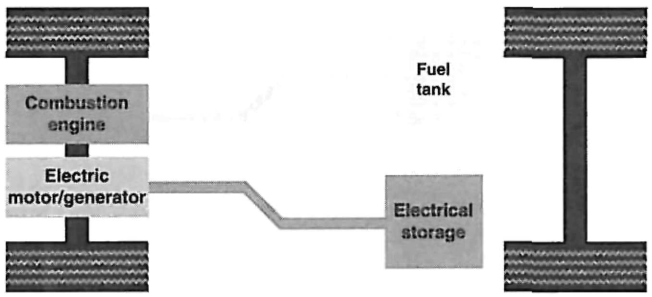


Fig. 2: Parallel HEV

As shown in Fig. 3, split-power hybrid cars utilize a combination of series and parallel drives (Bosch, 5th ed., 2007). These cars use a planetary gear (3) as a split-power transmission to allow some of the ICE power to be applied mechanically to the drive. The other part is converted into electrical energy through the alternator (7) and the inverter (5) to feed the electric motor (downstream of the transmission) and/or to charge the high-voltage battery (6). Depending upon driving conditions, the ICE, the electric motor, or both propel the vehicle.

1. internal-combustion engine; 2. tank
3. planetary gear; 4. electric motor; 5. inverter;
6. battery; 7. alternator.

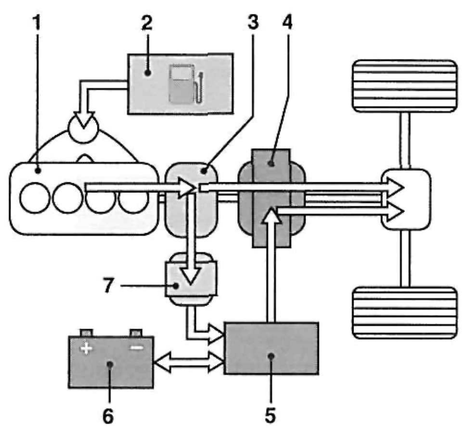


Fig. 3: Split power HEV

The functional block diagrams developed for these HEVs indicated that the speed of a vehicle depends upon the balance between the motive forces (developed by the gasoline engine and/or the electric motor) and running resistive forces. The resistive forces include the aerodynamic drag, rolling resistance, and climbing resistance. Fig. 4 illustrates the running resistances for a car moving uphill *(Bosch, 2007).*

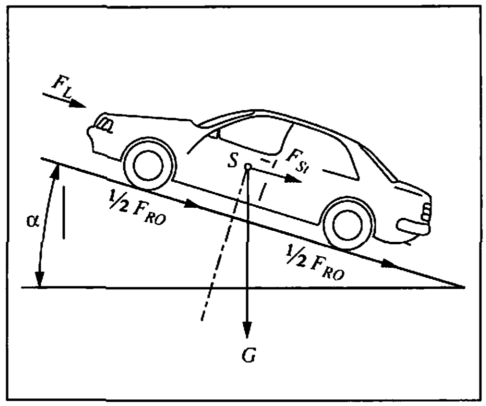


Fig. 4: Car moving uphill

The total running resistance, F_W is calculated as $F_w = F_{R_0} + F_L + F_{St}$, where F_{R_0} is the rolling resistance, F_L is the aerodynamic drag, and F_{St} is the climbing resistance. The aerodynamic drag is proportional to the square of the sum of car velocity, v, and the head-wind velocity, v_{hw}, or $v + v_{hw}$. The other two resistances are functions of car weight, G, and the gradient of the road (given by the gradient angle, α), as seen from the following equations:

$$F_{R0} = fG\cos\alpha = fmg\cos\alpha$$

where, f = coefficient of rolling resistance, m = car mass in kg, g = gravitational acceleration in m/s^2.

$$F_L = 0.5\rho C_w A\left(v + v_{hw}\right)^2$$

where, ρ = air density in kg/m^3, C_w = coefficient of aerodynamic drag, A = largest cross-section of the car in kg/m^2.

$$F_{St} = G\sin\alpha = mg\sin\alpha$$

The motive force, F, available at the drive wheel is:

$$F = \frac{Ti_{tot}}{r}\eta_{tot} = \frac{P\eta_{tot}}{v}$$

where, T = motive torque, P = motive power, i_{tot} = total transmission ratio, r = tire radius and η_{tot} = total drive train efficiency.

The surplus force, $F - F_w$, accelerates the vehicle (or retards it when $F_w > F$). Letting $a = \frac{F - F_w}{k_m m}$,

where a is the acceleration and km is a coefficient that compensates for the apparent increase in vehicle mass due to rotating masses.

CSQ-1 Show that car acceleration, a, may be determined from the equation:

$$F = fmg\cos\alpha + mg\sin\alpha + 0.5\rho C_w A\left(v + v_{hw}\right)^2 + k_m ma$$

CSQ-2 Assuming constant acceleration and using the average value for speed, find the average motive force, F_{av} (in N), and power, P_{av} (in kW) the car needs to accelerate from 40 to 60 km/h in 4 seconds on a level road, (α=0°), under windless conditions, where $v_{hw} = 0$. You are given the following parameters: m = 1590 kg, A = 2 m^2, f = 0.011, ρ = 1.2 kg/m^3, C_w = 0.3, η_{tot} = 0.9, k_m = 1.2. Furthermore, calculate the additional power, P_{add}, the car needs after reaching 60 km/h to maintain its speed while climbing a hill with a gradient α = 5°.

CSQ-3 The equation derived in **CSQ-2** describes the nonlinear car motion dynamics, where *F(t)* is the input to the system, and v(t) the resulting output. Given that the aerodynamic drag is proportional to v^2 under windless conditions, linearize the resulting equation of motion around an average speed, v_0 = 50 km/h, when the car travels on a level road, where α = 0°. (Hint: Expand v^2 –

v_0^2, in a truncated Taylor series). Write that equation of motion and represent it with a block diagram in which the block G_v represents the vehicle dynamics. The output of that block is the car speed, v(t), and the input is the excess motive force, $F_e(t)$, defined as: $F_e = F - F_{St} - F_{R0} + F_0$, where F_0 the constant component of the linearized aerodynamic drag.

CSQ-4 Use the equation in Part **c** to find the vehicle transfer function: $G_V(s) = V(s)/F_e(s)$.

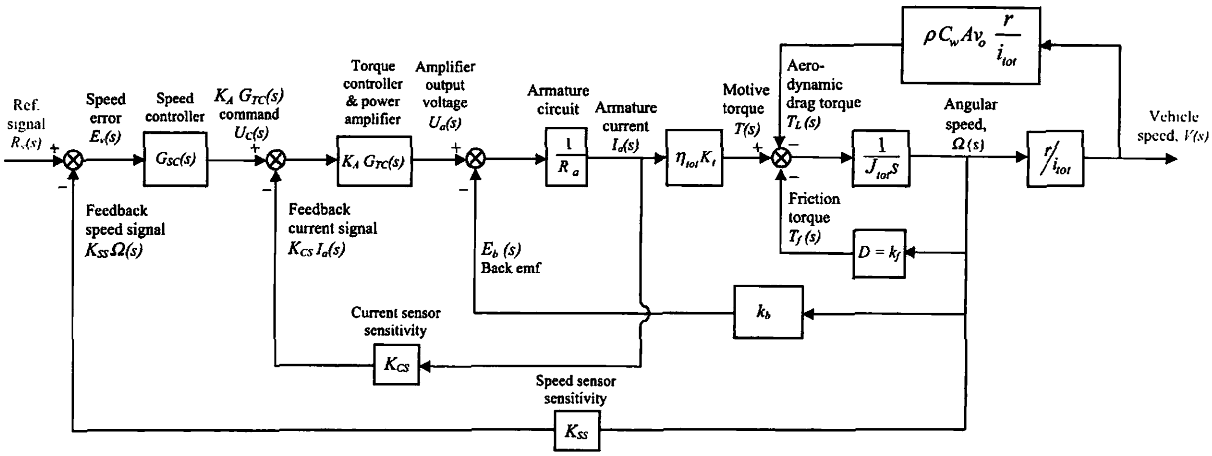


Fig. 5: Block diagram of cascade control for HEV

Fig. 5 shows the block diagram of a possible cascade control scheme for an HEV driven by a dc motor (Preitl, 2007). Let the speed controller $G_{SC}(s) = 100 + \frac{40}{s}$, the torque controller and power amp $K_A G_{TC}(s) = 10 + \frac{6}{s}$, the current sensor sensitivity $K_{CS} = 0.5$, the speed sensor sensitivity $K_{SS} = 0.0433$, $1/R_a = 1$, $\eta_{tot} K_t = 1.8$, kb = 2, $D = k_f = 0.1$, $J_{tot} = 7.226$, $r/i_{tot} = 0.0615$, and $\rho C_w A v_0 (r/i_{tot}) = 0.6154$.

CSQ-5 Find the transfer function $T(s) = V(s)/R_v(s)$ using block diagram reduction technique.

CSQ-6 Rearrange the block diagram shown in Fig. 5 as a unity feedback system, such that the output is $Y(s) = K_{SS}V(s)$ and forward path contains $G_{SC}(s)$ and G(s), i.e. speed controller and HEV dynamics respectively. Show that $G(s) = \frac{0.11(s+0.6)}{s(s+0.5173)+5(s+0.6)(s+0.01908)}$.

CSQ-7 If $G_{SC}(s)$ is a proportional controller, find the value of gain K_{PSC} that will result in critically damped system response. Use MATLAB/SCILAB to evaluate rise time, settling time with this controller. Compare performance with uncompensated system (i.e. $G_{SC}(s) = 1$).

CSQ-8 Now assume that the system specifications require zero steady-state error for step inputs, a steady-state error for ramp inputs < 2%, a M_P < 4.32%, and a settling time < 4 sec. Thus, start by designing a PI controller to meet the requirements. If necessary, add a PD mode to get a PID controller. Simulate your final design using MATLAB/SCILAB and check if all the performance specifications are satisfied or not.

CSQ-9 Suppose, you designed a PID controller in the previous example. Can you think of a way in which you can design only a PI controller and yet achieve similar performance?

CSQ-10 Design a lead compensator for the specifications given in **CSQ-8**. Check if your design gives satisfactory performance. Compare its performance with PID/PI controller designed earlier.

The case study is based on: Preitl, Z., Bauer, P., and Bokor, J., “A Simple Control Solution for Traction Motor Used in Hybrid Vehicles.” 4^{th} *International Symposium on Applied Computational Intelligence and Informatics.* I E E E , 2007.