

Linear Systems TTK4115 - Helicopter lab

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1 Part 1 - Mathematical modeling

1.1 Problem 1

We use the helicopter model shown in fig. 1 and fig. 2 as our starting point for deriving the equations of motion.

Figure 1: the helicopter model figure 7 from the assignment depicting forces and joint axes [2, p.12].

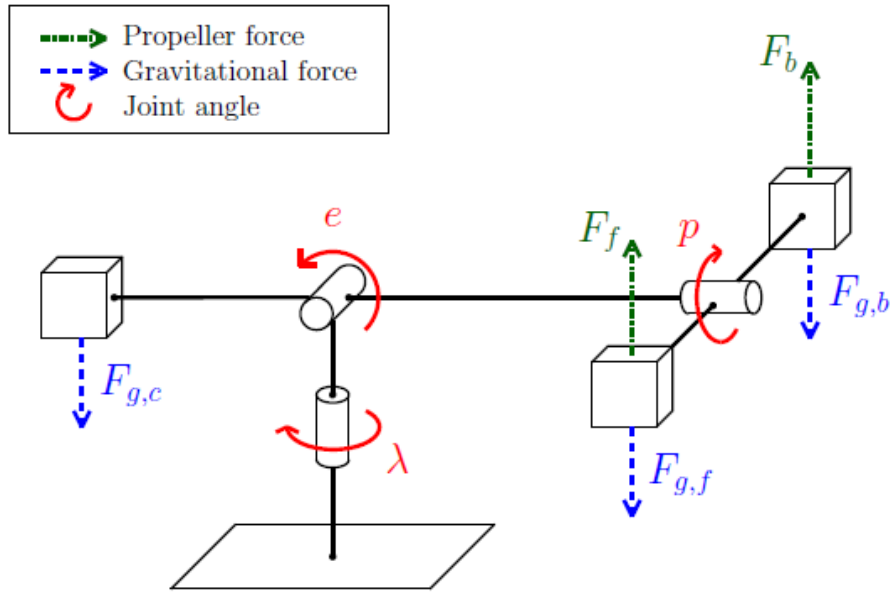
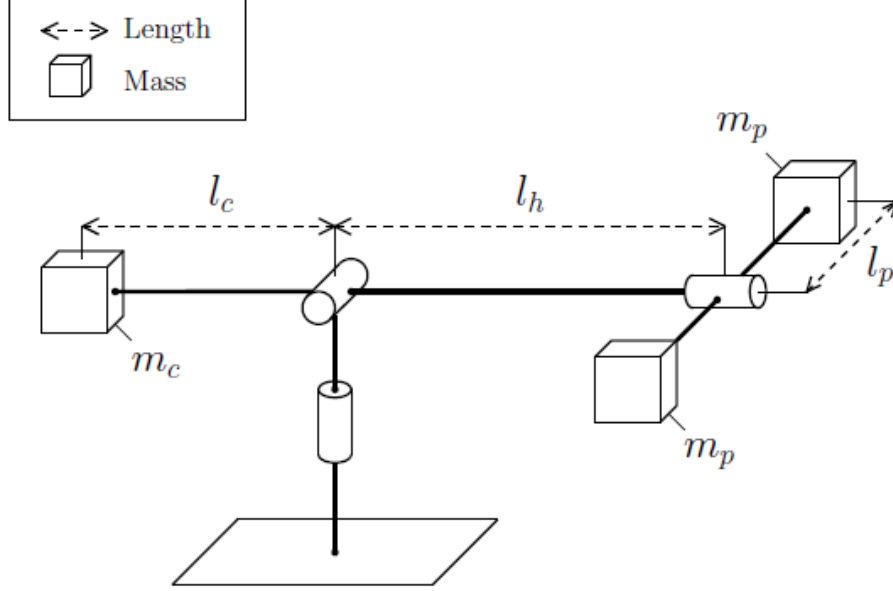


Figure 2: the helicopter model figure 8 from the assignment depicting masses and distances between the joint axes and the point masses [2, p.13].



The equation of motion for the pitch is found through the momentum around the pitch axis in the clockwise direction as shown in fig. 1. It becomes:

$$\begin{aligned} J_p \ddot{p} &= l_p (F_{g,b} - F_b - F_{g,f} + F_f) \\ &= l_p (m_p g - m_p g + K_f V_f - V_b) \\ &= l_p K_f (V_f - V_b) \end{aligned}$$

Where the lengths including l_p is shown in fig. 2. Since $V_d = V_f - V_b$, we can write this as:

$$J_p \ddot{p} = l_p K_f V_d \quad (1)$$

Therefore $L_1 = l_p K_f$.

The equation of motion for the elevation angle is found similarly through the momentum in the counter-clockwise direction around the elevation axis, again as shown in fig. 1. Only the vertical forces in the helicopter model have an arm of moment around the elevation axis.

$$J_e \ddot{e} = \text{arm}_c F_{g,c} - \text{arm}_h (F_{g,f} + F_{g,b} - (F_{f,v} + F_{b,v}))$$

where arm_c is the moment arm between the counterweight point mass and the elevation axis, and arm_h is the moment arm between any of the two motor point masses and the elevation axis, which also is the moment arm for the components of the two motor forces perpendicular to the elevation axis. $F_{f,v}$ is the vertical component of F_f , and $F_{b,v}$ is the vertical component of F_b . As shown in fig. 3, $\text{arm}_c = l_c \cos(e)$, and $\text{arm}_h = l_h \cos(e)$.

Figure 3: moment arms around the elevation axis. Also, the positive direction of momentum is displayed as counter-clockwise around the e-axis.

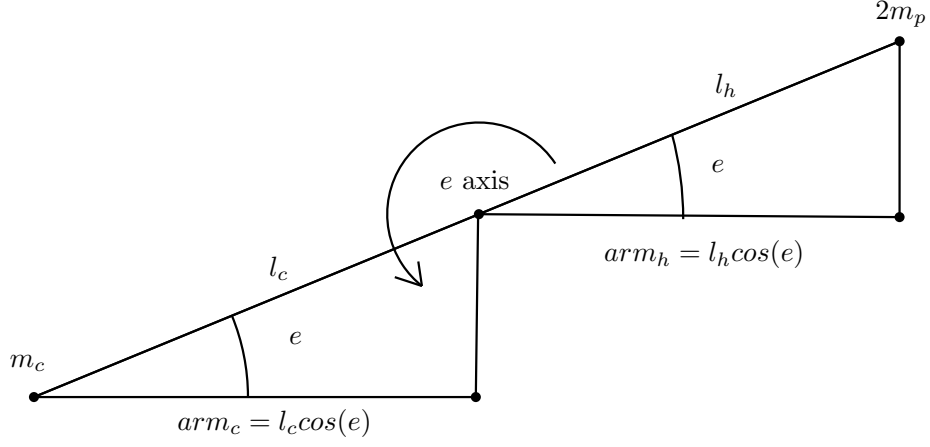
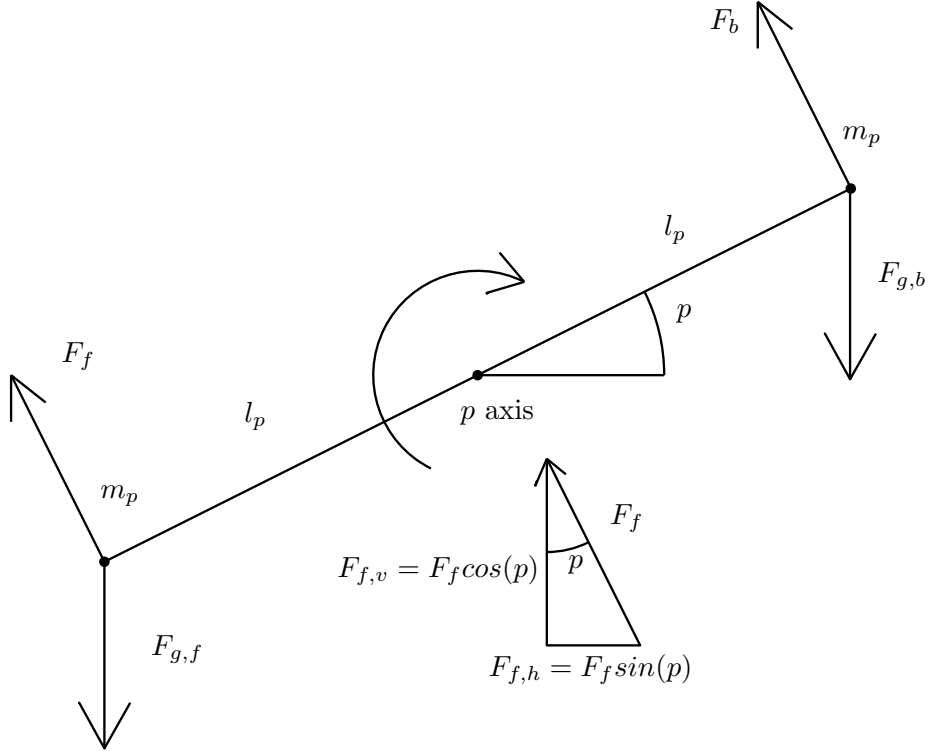


Figure 4: gravitational and motor forces on the helicopter head, as well as the decomposition of the motor forces into vertical and horizontal components.



As shown in fig. 4, the vertical component of the motor forces $F_{f,v}$ and $F_{b,v}$ are

$F_f \cos(p)$ and $F_b \cos(p)$ respectively.

$$\begin{aligned} J_e \ddot{e} &= \text{arm}_c F_{g,c} - \text{arm}_h (F_{g,f} + F_{g,b} - \cos(p)(F_f + F_b)) \\ &= \text{arm}_c m_c g - \text{arm}_h (m_p g + m_p g - K_f \cos(p)(V_f + V_b)) \end{aligned}$$

We substitute in $V_s = V_f + V_b$ and the two moment arms:

$$\begin{aligned} J_e \ddot{e} &= l_c \cos(e) m_c g - l_h \cos(e) (2m_p g - K_f \cos(p) V_s) \\ &= \cos(e) (l_c m_c g - 2l_h m_p g) + l_h K_f V_s \cos(e) \cos(p) \end{aligned}$$

Here, we have (as the author of the exercise [2]) counted the $\cos(e)$ factor of the V_s term as negligible, and set it to 1.

Ser nå at neglisjeringen av $\cos(e)$ for de to motorkreftene ikke er en neglisjering i det hele tatt. De har ikke en $\cos(e)$ faktor fordi deres retning forandrer seg med e , slik at de alltid er vinkelrette med lengde l_h

The resulting equation has the form:

$$J_e \ddot{e} = g(l_c m_c - 2l_h m_p) \cos(e) + l_h K_f V_s \cos(p) \quad (2)$$

We see that $L_2 = g(l_c m_c - 2l_h m_p)$, and $L_3 = l_h K_f$.

Finally, the equation of motion for the travel angle is found through the momentum around the travel axis in the clockwise direction, as shown in fig. 1. As seen in fig. 4, the only forces with a moment arm perpendicular to the travel axis are the components of the motor forces in the horizontal direction, $F_{f,h} = F_f \sin(p)$ and $F_{b,h} = F_b \sin(p)$, has fig. 3 have the moment arm of length $\text{arm}_h = l_h \cos(e)$:

$$\begin{aligned} J_\lambda \ddot{\lambda} &= \text{arm}_h (F_{f,h} + F_{b,h}) \\ &= l_h \cos(e) (K_f \sin(p) (V_f + V_b)) \end{aligned}$$

Again substituting $V_s = V_f + V_b$, and we get the final equation of motion:

$$J_\lambda \ddot{\lambda} = l_h K_f V_s \cos(e) \sin(p) \quad (3)$$

We see that $L_4 = l_h K_f$.

The equations eq. (1), eq. (2), and eq. (3) correspond to equations (2a), (2b), and (2c) respectively from the assignment [2, p.13], and it has been shown .

QED?

1.2 Problem 2

To linearize the system about the point with all state variables equal to zero ($(p, e, \lambda)^T = (\dot{p}, \dot{e}, \dot{\lambda})^T = (0, 0, 0)$) the inputs in the equations of motion (V_s^* and V_d^*) must be set to values that make this an equilibrium point.

At the linearization point, the equation of motion for pitch, eq. (1), reduces to $0 = L_1 * V_d^*$ therefore:

$$V_d^* = 0 \quad (4)$$

At the linearization point, the equation of motion for elevation, eq. (2), reduces to $0 = L_2 + L_3 * V_s^*$ therefore:

$$V_s^* = -L_2/L_3 \quad (5)$$

While the equation of motion for travel () at the linearization point simply reduces to $0 = 0$. The following transformation is performed to simplify the analysis [2, p.14]:

$$\begin{bmatrix} \tilde{p} \\ \tilde{e} \\ \tilde{\lambda} \end{bmatrix} = \begin{bmatrix} p \\ e \\ \lambda \end{bmatrix} - \begin{bmatrix} p^* \\ e^* \\ \lambda^* \end{bmatrix} \text{ and } \begin{bmatrix} \tilde{V}_s \\ \tilde{V}_d \end{bmatrix} = \begin{bmatrix} V_s \\ V_d \end{bmatrix} - \begin{bmatrix} V_s^* \\ V_d^* \end{bmatrix} \quad (6)$$

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The equations of motion in the transformed system are therefore:

$$J_p \ddot{\tilde{p}} = L_1 \tilde{V}_d \quad (7a)$$

$$J_e \ddot{\tilde{e}} = L_2 \cos(\tilde{e}) + L_3(\tilde{V}_s + L_2/L_3) \cos(\tilde{p}) \quad (7b)$$

$$J_\lambda \ddot{\tilde{\lambda}} = L_4(\tilde{V}_s + L_2/L_3) \cos(\tilde{e}) \sin(\tilde{p}) \quad (7c)$$

By choosing the state to be $x = (\tilde{p}, \tilde{e}, \tilde{\lambda}, \dot{\tilde{p}}, \dot{\tilde{e}}, \dot{\tilde{\lambda}})$ the nonlinear state equations become:

$$\dot{x}_1 = x_4 \quad (8a)$$

$$\dot{x}_2 = x_5 \quad (8b)$$

$$\dot{x}_3 = x_6 \quad (8c)$$

$$\dot{x}_4 = (L_1/J_p) V_d \quad (8d)$$

$$\dot{x}_5 = (L_2/J_e) \cos(x_2) + (L_3/J_e)(V_s + L_2/L_3) \cos(x_1) \quad (8e)$$

$$\dot{x}_6 = (L_4/J_\lambda)(V_s + L_2/L_3) \cos(x_2) \sin(x_1) \quad (8f)$$

If the above system is expressed as $\dot{x} = h(x, u)$, where x is the state and u is the input, the system is linearized by finding the Jacobians of h with respect to the state and the input and then plugging in the equilibrium values.

$$\frac{\partial h}{\partial x} = A = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{L_4 L_2}{J_\lambda L_3} & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad \frac{\partial h}{\partial u} = B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & L_1/J_p \\ L_3/J_e & 0 \\ 0 & 0 \end{bmatrix} \quad (9)$$

where L_1, L_2, L_3 and L_4 were calculated in Section 1.1 and J_p, J_e and J_λ were given in the assignment description [2, p.14]. The linearized equations of motion can therefore be written in the following form:

$$\ddot{\tilde{p}} = K_1 \tilde{V}_d \quad K_1 = \frac{L_1}{J_p} \quad (10a)$$

$$\ddot{\tilde{e}} = K_2 \tilde{V}_s \quad K_2 = \frac{L_3}{J_e} \quad (10b)$$

$$\ddot{\tilde{\lambda}} = K_3 \tilde{p} \quad K_3 = \frac{L_4 L_2}{J_\lambda L_3} \quad (10c)$$

1.3 Problem 3

Check if we added gain to the output of joystick

The helicopter is difficult to control using only feed-forward. The physical behaviour of the helicopter differs from the (2a) - (2c) [2, p.13] model because it does not take into consideration air resistance drag, ground effects nor the changes in length of the moment arm around the elevation axis.

In eq. (10) the model is linearized around a point with all angles equal to zero, where elevation is defined as zero when the elevation arm is parallel to the table, pitch is defined as zero when the pitch arm is parallel to the table and travel angle is defined as zero at the initial travel angle. Since the physical system is not linear, the linear assumption breaks down when the system is too far from this point.

1.4 Problem 4

Elevation is the only variable that needs to be changed, since travel and pitch are zeroed correctly upon initialization. To correct for the offset of the arm at startup, subtract 30 degrees from the elevation to get the correct point of zero elevation.

The value of V_s^* in order to stabilize the helicopter at the equilibrium point, was measured to be 7.5 V.

The motor force constant, K_f , which relates F_f and V_f is calculated to be $-(L_2/l_h) * V_s^*$, and has the value 0.1332.

2 Part 2 – Monovariable control

2.1 Problem 1

The following controller form is given in the assignment[2, p.15]:

$$\ddot{V}_d = K_{pp}(\tilde{p}_c - \tilde{p}) - K_{pd}\dot{\tilde{p}} \quad (11)$$

Substituting in the equation for pitch angle (eq. (1)) gives the following.

$$\ddot{\tilde{p}} = K_1 K_{pp}(\tilde{p}_c - \tilde{p}) - K_1 K_{pd}\dot{\tilde{p}} \quad (12)$$

To find the transfer function, $\frac{\tilde{p}(s)}{\tilde{p}_c(s)}$, the Laplace transform is taken.

$$\begin{aligned} \ddot{\tilde{p}} + K_1 K_{pd}\dot{\tilde{p}} + K_1 K_{pp}\tilde{p} &= K_1 K_{pp}\tilde{p}_c \\ \mathcal{L} \rightarrow \\ s^2\tilde{p}(s) + sK_1 K_{pd}\tilde{p}(s) + K_1 K_{pp}\tilde{p}(s) &= K_1 K_{pp}\tilde{p}_c(s) \end{aligned}$$

Which gives the transfer function

$$\frac{\tilde{p}(s)}{\tilde{p}_c(s)} = \frac{K_1 K_{pp}}{s^2 + K_1 K_{pd}s + K_1 K_{pp}} \quad (13)$$

The linearized pitch dynamics can be regarded as a second-order linear system, which means that by putting eq. (13) in the form shown in eq. (14), K_{pp} and K_{pd} can be determine from ω and ζ .

$$h(s) = \frac{\omega^2}{s^2 + 2\zeta\omega s + \omega^2} \quad (14)$$

This gives the following relations:

$$\omega = \sqrt{K_1 K_{pp}} \quad (15)$$

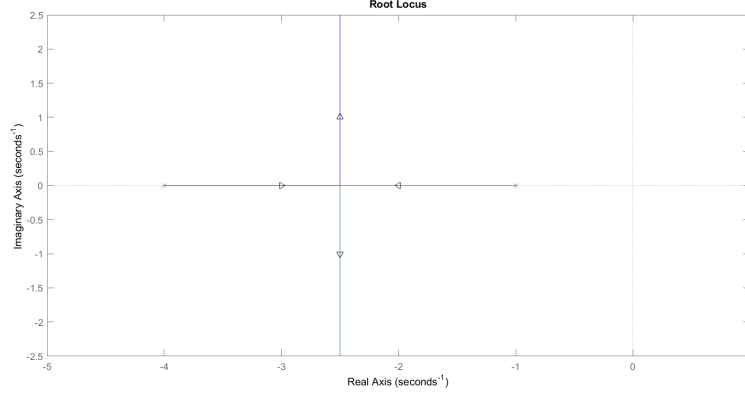
$$\begin{aligned} 2\zeta\omega^2 &= K_1 K_{pd} \\ \zeta &= \frac{K_1 K_{pd}}{2\omega^2} = \frac{K_{pd}}{2K_{pp}} \end{aligned} \quad (16)$$

For a critically damped system $\zeta = 1$, which gives the following relationship

$$K_{pd} = 2K_{pp} \quad (17)$$

Beginning with a $K_{pp} = 3$, and then from the relation in eq. (17) a $K_{pd} = 6$, the response of the pitch angle to the input was slower than desired. Therefore, K_{pp} was increased to $K_{pp} = 12.5$ and K_{pd} was lowered to underdamp the system, until it was sufficiently responsive at $K_{pd} = 0.7K_{pp} = 8.75$. At these values the system responded faster with only minor oscillations. It was observed that larger values of K_{pp} gave rise to larger oscillations.

Figure 5: Change in pole position by increasing K_{pp} given a constant K_{pd}



At the critically damped point, the poles lie on the same point on the x-axis. When K_{pp} is decreased in relation to K_{pd} the system is over-damped the poles move away from each other along the x-axis. When K_{pp} is increased in relation to K_{pd} , the system is under damped and the poles move away from each other vertically from the critically damped point.

With the PD controller, it was significantly easier to control the helicopter than with just feed forward joystick control as no scaling of the joystick input was needed.

2.2 Problem 2

By plugging the P controller for travel

$$\tilde{p} = K_{rp}(\dot{\tilde{\lambda}}_c - \dot{\tilde{\lambda}}) \quad (18)$$

into the equation of motion for travel eq. (10c), the transfer function between $\dot{\tilde{\lambda}}$ and $\dot{\tilde{\lambda}}_c$ can be derived. By substituting the right side of the controller into the equation of motion for travel the equation becomes:

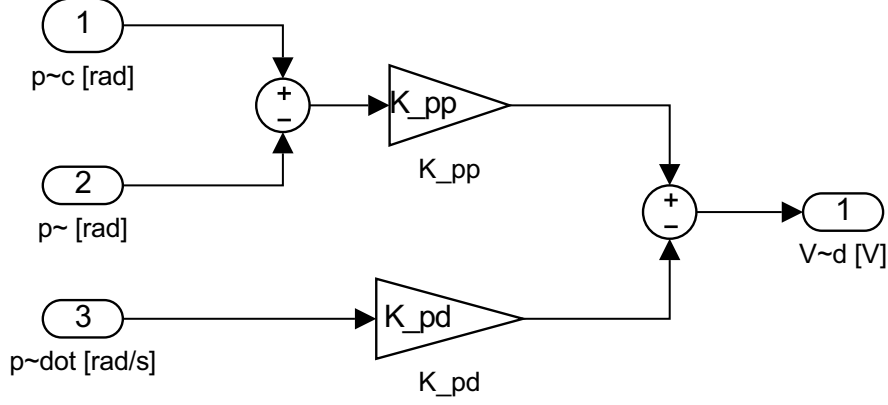
$$\ddot{\tilde{\lambda}} = K_3(K_{rp}(\dot{\tilde{\lambda}}_c - \dot{\tilde{\lambda}})) \quad (19)$$

After taking the laplace transform and rearranging terms, the transfer function is as follows:

$$\frac{\dot{\tilde{\lambda}}(s)}{\dot{\tilde{\lambda}}_c(s)} = \frac{K_3 K_{rp}}{s + K_3 K_{rp}} \quad (20)$$

This controller was quite quick and stable after correctly tuning K_{rp} . The value that was deemed best was $K_{rp} = -2$. Higher values, or more negative values, of K_{rp} led to large oscillations, while lower values, or less negative values, of K_{rp} led to a slower response to the joysticks input. It was not necessary to add a gain to the x value of the joystick to produce quick and accurate control.

Figure 6: Simulink implementation of PD controller



3 Part 3 - Multivariable control

3.1 Problem 1

Here, we are to find the systems matrices \mathbf{A} and \mathbf{B} . Trivially, they are:

$$\mathbf{A} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} 0 & 0 \\ 0 & K_1 \\ K_2 & 0 \end{bmatrix} \quad (21)$$

3.2 Problem 2

First, we are to examine the controllability of the system. We do that by finding the controllability matrix \mathbf{C} of the system, and see whether it has full rank or not:

$$\mathbf{C} = [\mathbf{B} \quad \mathbf{AB}] = \begin{bmatrix} 0 & 0 & 0 & K_1 \\ 0 & K_1 & 0 & 0 \\ K_2 & 0 & 0 & 0 \end{bmatrix} \quad (22)$$

which has full rank: $\text{rank}(\mathbf{C}) = 3$, and is thus controllable.

Second, we are to implement a LQR controller with reference feed-forward. Our \mathbf{P} is defined such that as time goes to infinity, our states \tilde{p} and $\dot{\tilde{e}}$ tend to their reference values \tilde{p}_c and $\dot{\tilde{e}}_c$. This happens when $\dot{\mathbf{x}} = 0$, as the system reaches a stable equilibrium around the reference values:

$$\begin{aligned} \dot{\mathbf{x}} &= \mathbf{Ax} + \mathbf{Bu} \\ &= \mathbf{Ax} + \mathbf{B}(\mathbf{Pr} - \mathbf{Kx}) \\ &= (\mathbf{A} - \mathbf{BK})\mathbf{x} + \mathbf{BPr} = 0 \end{aligned}$$

When $\dot{\mathbf{x}} = 0$, our \mathbf{x} has reached its final value and we define $\mathbf{x} = \mathbf{x}_\infty$:

$$\begin{aligned} (BK - A)\mathbf{x}_\infty &= BPr \\ \Leftrightarrow \mathbf{x}_\infty &= (BK - A)^{-1}BPr \\ \Rightarrow \mathbf{y}_\infty &= C\mathbf{x}_\infty = C(BK - A)^{-1}BPr \end{aligned}$$

We see that our output \mathbf{y}_∞ is equal to our reference \mathbf{r} when:

$$P = [C(BK - A)^{-1}B]^{-1} \quad (23)$$

Therefore, we now have

$$\lim_{t \rightarrow \infty} \mathbf{y}(t) = \mathbf{y}_\infty = \begin{bmatrix} \tilde{p} \\ \dot{\tilde{e}} \end{bmatrix} = \begin{bmatrix} \tilde{p}_c \\ \dot{\tilde{e}}_c \end{bmatrix} = \mathbf{r},$$

which is what we wanted.

3.3 Problem 3

Without integral effect, the system could track pitch without much of a problem. But the elevation rate had a noticeable deviation in the ranges of elevation not close to our linearization point $\dot{\tilde{e}} = 0$.

With integral effect, this deviation in elevation rate is asymptotically removed. This means that with a zero Y output from our joystick, we see a corresponding zero elevation rate, and the elevation angle stays asymptotically constant also for angles not close to its linearization point.

4 Part 4 – State estimation

This section consists of the development of an observer to estimate the nonmeasured angular velocities.

4.1 Problem 1

By describing the system in eq. (10) in the following state-space form

$$\begin{aligned}\dot{\mathbf{x}} &= \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \\ \mathbf{y} &= \mathbf{C}\mathbf{x}\end{aligned}\tag{24}$$

where \mathbf{A} , \mathbf{B} and \mathbf{C} are matrices. The state -, input - and output vector are given by

$$\mathbf{x} = \begin{bmatrix} \tilde{p} \\ \dot{\tilde{p}} \\ \tilde{e} \\ \dot{\tilde{e}} \\ \tilde{\lambda} \\ \dot{\tilde{\lambda}} \end{bmatrix}, \quad \mathbf{u} = \begin{bmatrix} \tilde{V}_s \\ \tilde{V}_d \end{bmatrix} \quad \text{and} \quad \mathbf{y} = \begin{bmatrix} \tilde{p} \\ \tilde{e} \\ \tilde{\lambda} \end{bmatrix}\tag{25}$$

This gives the following \mathbf{A} , \mathbf{B} and \mathbf{C} matrices

$$\mathbf{A} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ K_3 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} 0 & 0 \\ 0 & K_1 \\ 0 & 0 \\ K_2 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \quad \text{and} \quad \mathbf{C} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}\tag{26}$$

Where K_1 , K_2 and K_3 are given by eq. (10).

4.2 Problem 2

4.3 Problem 3

References

- [1] Chi-Tsong Chen, *Linear System Theory and Design*, Oxford University Press, 4th edition, 2014
- [2] Kristoffer Gryte et al., *Helicopter lab assignment*, Department of Engineering Cybernetics, NTNU, Version 4.5, 2015