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Universiti Tun Hussein Onn Malaysia

UNIVERSITI TUN HUSSEIN ONN MALAYSIA

FINAL EXAMINATION
SEMESTER II
SESSION 2020/2021

COURSE NAME	:	ELECTROMECHANICAL AND CONTROL SYSTEMS
COURSE CODE	:	BDU 20302
PROGRAMME	:	BDC / BDM
EXAMINATION DATE	:	JULY 2021
DURATION	:	3 HOURS
INSTRUCTION	:	ANSWER **FOUR (4)** QUESTIONS **ONLY**

THIS QUESTION PAPER CONSISTS OF **TEN (10)** PAGES

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Q1 An autopilot that controls an aircraft in the roll axis only are also known as wing levelers reflecting their single capability. Consider a roll autopilot of a jet fighter shown in **Figure Q1(a).**

(a) Determine the closed-loop transfer function $\phi(s)/\phi_d(s)$ if $K_g = 0.5$.

(5 marks)

(b) Determine the roots of the characteristic equations if the controller gain is set at $K = 2$, 5 and 7.

(3 marks)

(c) Using the concept of dominant roots, differentiate the effect of gain selection (i.e. $K = 2$, 5 and 7) towards the closed-loop system's time response. Suggest the range of gain values that will make the control system unstable.

(9 marks)

(d) Determine a suitable controller gain, K, so that the closed-loop system's percentage overshoot is equal to 16%. Calculate the resulting peak time.

(8 marks)

Q2 (a) The short-period response characteristics of an aircraft are of particular importance in flying and handling quality. The reduced-order state-space model corresponding to short-period mode approximation for the Ultrastick-25e fixed-wing UAV aircraft are given as follows:

$$\begin{bmatrix} \dot{w} \\ \dot{q} \end{bmatrix} = \begin{bmatrix} Z_w & Z_q \\ M_w & M_q \end{bmatrix} \begin{bmatrix} w \\ q \end{bmatrix} + \begin{bmatrix} Z_{\delta_e} \\ M_{\delta_e} \end{bmatrix} \delta_e$$

with the following stability derivatives:

$$Z_w = -7.56 \qquad M_q = -15.81$$
$$Z_q = 15.72 \qquad Z_{\delta_e} = -2.703$$
$$M_w = -7.406 \qquad M_{\delta_e} = -133.7$$

Find the solution to the given state-space model using Paynter's numerical method. Use time interval, $\Delta t = 0.01$ to solve the numerical problem.

(6 marks)

(b) If the input of the system, u_1 is applied with 1° elevator step input with output equation and initial condition given as follows:

$$q_k = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} w_k \\ q_k \end{bmatrix}$$
$$\begin{bmatrix} w_0 \\ q_0 \end{bmatrix} = \begin{bmatrix} 1.5 \\ 0.15 \end{bmatrix}$$

Determine the output response, q_k of the state equation for three (3) iterations.

(6 marks)

(c) Comment on the handling quality performance of the short period motion obtained for this aircraft. Do your findings agree with the handling quality criteria shown in **Figure Q2(c)**?

(8 marks)

(d) Examine the stability derivatives influence on the damping ratio and natural frequency of the short period motion.

(5 marks)

Q3 Consider a pitch control system is shown in **Figure Q3** with transfer functions for each component in the control system are given as:

$$K(s) = K_P + \frac{K_I}{s} + K_D s$$

$$G_2(s) = \frac{-6.5}{s^2 + 0.3s + 2.2}$$

(a) Determine the time response performance of the open-loop system and comment on any problem with the system.

(3 marks)

(b) Design the PD and PID controllers for the pitch control system to exhibit satisfactory transient response with 16% overshoot and settling time less than 2.6 s.

(17 marks)

(c) Compare the steady-state error performance of the compensated systems (i.e. PD and PID control). Which controller produces the best performance in terms of steady-state error.

(5 marks)

Q4 (a) Describe the physical characteristics of Dutch Roll stability mode.

(3 marks)

(b) The Dutch Roll motion can be approximated using the following equation:

$$\begin{bmatrix} \Delta\dot{\beta} \\ \Delta\dot{r} \end{bmatrix} = \begin{bmatrix} \frac{Y_\beta}{u_0} & -\left(1 - \frac{Y_r}{u_0}\right) \\ N_\beta & N_r \end{bmatrix} \begin{bmatrix} \Delta\beta \\ \Delta r \end{bmatrix} + \begin{bmatrix} \frac{Y_{\delta r}}{u_0} \\ N_{\delta r} \end{bmatrix} \delta r$$

Assume the aircraft has the following stability derivative characteristics as follows:

$Y_\beta = -7.5$ ft/s^2 $\quad$ $Y_r = 3.1$ ft/s

$N_\beta = 3.9$ s^{-2} $\quad$ $N_r = -0.35$ s^{-1}

$Y_{\delta r} = -5.9$ ft/s^2 $\quad$ $N_{\delta r} = 0.515$ s^{-2}

$u_0 = 120$ ft/s

(i) Determine the characteristic equation of the Dutch Roll mode.

(4 marks)

(ii) Determine the eigenvalues of the Dutch Roll mode.

(2 marks)

(iii) Determine the damping ratio, natural frequency, period, time to half amplitude, and the number of cycles to half amplitude for the Dutch Roll mode.

(5 marks)

(c) The roll angle to aileron input transfer function can be modelled according to:

$$\frac{\phi(s)}{\delta_a(s)} = \frac{L_{\delta a}}{s(s - L_p)}$$

Design a roll attitude control system to maintain a wings-level attitude for a vehicle having the following characteristics:

$$L_{\delta a} = 2.5/s^2$$
$$L_p = -0.5/s^2$$

The system performance is to have a damping ratio, $\xi = 0.5$ and undamped natural frequency, $\omega_n = 3$ rad/s. Consider the sensor used in the control system design to be a perfect device.

(11 marks)

Q5 (a) Explain how the root locus plot can be used to evaluate the effect of feedback on the characteristic of motion?

(2 marks)

(b) An attitude control system for a satellite vehicle within the earth's atmosphere is shown in **Figure Q5**. The transfer functions of the system are given as follows:

$$G(s) = \frac{K(s + 0.2)}{(s + 0.9)(s - 0.6)(s - 0.1)}$$

$$G_c(s) = \frac{(s^2 + 4s + 6.25)}{(s + 4)}$$

Suggest a range of gain, *K*, that results in a system with a settling time less than 10 s and a damping ratio for the complex roots greater than 0.643. Provide a detailed root locus plot for the closed-loop system as *K* varies from 0 to ∞ with necessary calculation such as the asymptote angle, centroid, break-in/out, angle of departure/arrival or imaginary axis intersection point to support your answer.

(23 marks)

-END OF QUESTION-

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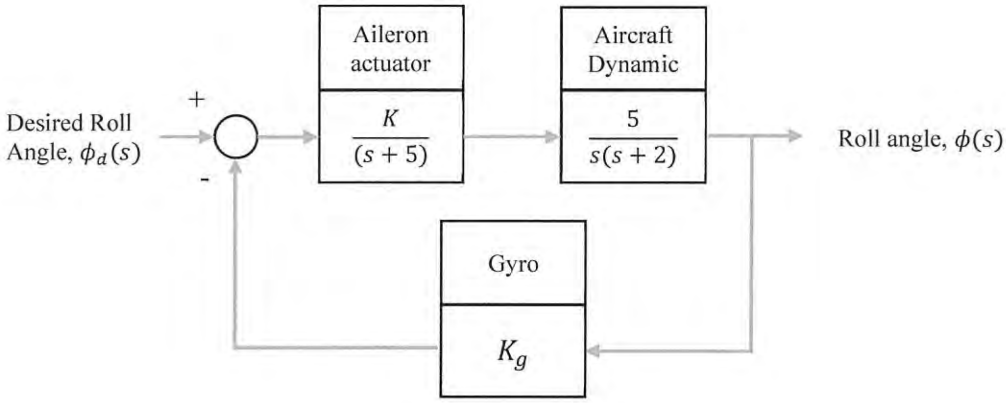

Figure Q1(a) Roll angle control system.

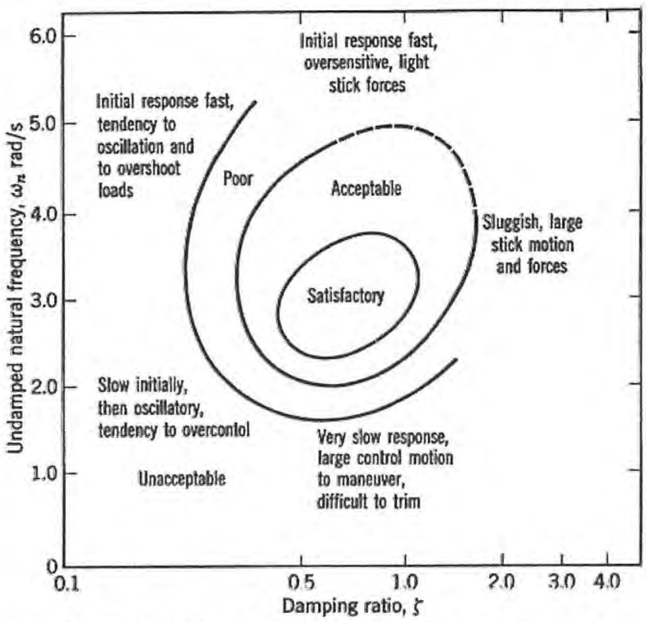

FIGURE Q2(c) The short period flying quality.

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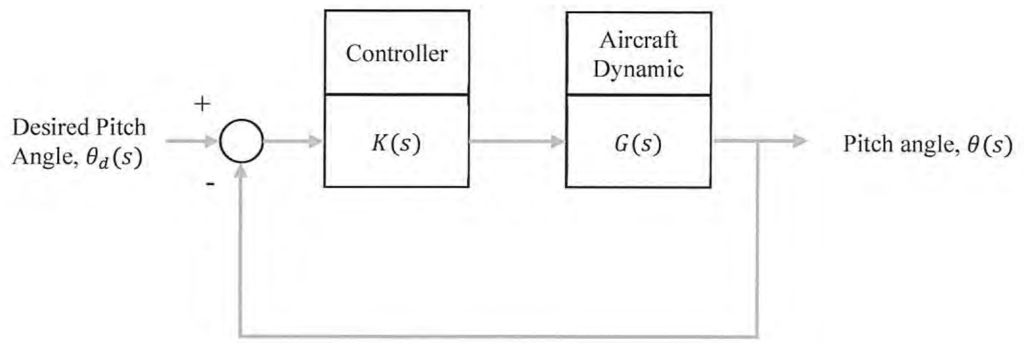

Figure Q3 Simplified block diagram for pitch angle control system.

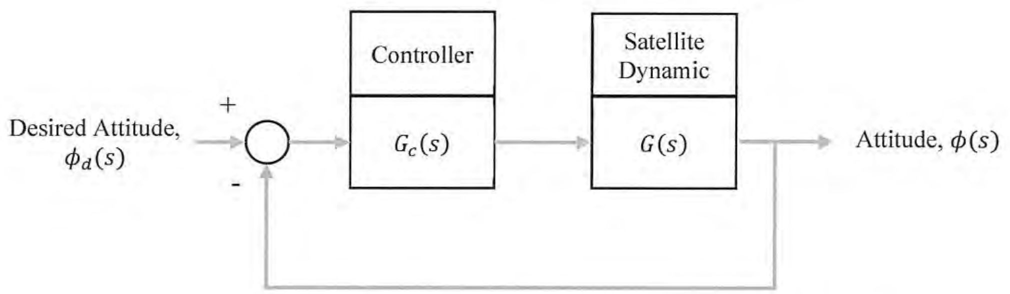

Figure Q5 The block diagram for the satellite control system.

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Key Equations

The relevant equations used in this examination are given as follows:

1. The determinant of a 3 × 3 matrix:
$$\begin{vmatrix} a & b & c \\ d & e & f \\ g & h & i \end{vmatrix} = a\begin{vmatrix} e & f \\ h & i \end{vmatrix} - b\begin{vmatrix} d & f \\ g & i \end{vmatrix} + c\begin{vmatrix} d & e \\ g & h \end{vmatrix} \quad (1)$$
2. Partial fraction for $F(s)$ with real and distinct roots in the denominator:
$$F(s) = \frac{K_1}{(s+p_1)} + \frac{K_2}{(s+p_2)} + \cdots + \frac{K_m}{(s+p_m)} \quad (2)$$
3. Partial fraction for $F(s)$ with complex or imaginary roots in the denominator:
$$F(s) = \frac{K_1}{(s+p_1)} + \frac{K_2 s + K_3}{(s^2+as+b)} + \cdots \quad (3)$$
4. General first-order transfer function:
$$G(s) = \frac{s}{s+a} \quad (4)$$
5. General second-order transfer function:
$$G(s) = \frac{K}{s^2 + 2\xi\omega_n s + \omega_n} \quad (5)$$
6. The closed-loop transfer function:
$$T(s) = \frac{G(s)}{1+G(s)H(s)} \quad (6)$$
where $G(s)$ is the transfer function of the open-loop system, and $H(s)$ is the transfer function in the feedback loop.
7. The final value theorem:
$$\lim_{t\to\infty} y(t) = \lim_{s\to 0} sY(s) \quad (7)$$
8. Time response:
$$T_r = \frac{2.2}{a} \quad (8)$$
$$T_s = \frac{4}{a} \quad (9)$$
$$\%OS = e^{-\left(\frac{\xi\pi}{\sqrt{1-\xi^2}}\right)} \times 100\% \quad (10)$$
$$\xi = \frac{-\ln\left(\%\frac{OS}{100}\right)}{\sqrt{\pi^2 + \left(\ln\left(\%\frac{OS}{100}\right)\right)^2}} \quad (11)$$

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$$T_p = \frac{\pi}{\omega_n\sqrt{1-\xi^2}} = \frac{\pi}{\omega} \quad (12)$$

$$T_s = \frac{4}{\xi\omega_n} = \frac{4}{\eta} \quad (13)$$

$$P = \frac{2\pi}{\omega} \quad (14)$$

$$t_{1/2} = \frac{0.693}{|\eta|} \quad (15)$$

$$N_{1/2} = 0.110\frac{|\omega|}{|\eta|} \quad (16)$$

9. Estimation of parameter q (Paynter Numerical Method)

$$q = \max|A_{ij}\Delta t| \quad (17)$$

10. Estimation of the integer value of p (Paynter Numerical Method)

$$\frac{1}{p!}(nq)^p e^{nq} \leq 0.001 \quad (18)$$

11. Numerical solution of state equation:

$$\mathbf{x}_{k+1} = \boldsymbol{M}\mathbf{x}_k + \boldsymbol{N}\boldsymbol{\eta}_k$$

with matrix $\boldsymbol{M}$ and $\boldsymbol{N}$ are given by the following matrix expansion:

$$\boldsymbol{M} = e^{A\Delta t} = \boldsymbol{I} + \boldsymbol{A}\Delta t + \frac{1}{2!}\boldsymbol{A}^2\Delta t^2 \ldots \quad (19)$$

$$\boldsymbol{N} = \Delta t\left(\boldsymbol{I} + \frac{1}{2!}\boldsymbol{A}\Delta t + \frac{1}{3!}\boldsymbol{A}^2\Delta t^2 + \cdots\right)\boldsymbol{B}$$

12. Characteristic equation of the closed loop system:

$$1 + KG(s)H(s) = 0 \quad (20)$$

13. Asymptotes: angle and real-axis intercept:

$$\sigma = \frac{[\sum Real\ parts\ of\ the\ poles - \sum Real\ parts\ of\ the\ zeros]}{n-m} \quad (21)$$

$$\phi_a = \frac{180°[2q+1]}{n-m} \quad (22)$$

14. The solution to determine real axis break-in and breakaway points:

$$\frac{dK(\sigma)}{d\sigma} = 0 \quad (23)$$

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15. An alternative solution to find real axis break-in and breakaway points:

$$\sum \frac{1}{\sigma + z_i} = \sum \frac{1}{\sigma + p_i} \quad (24)$$

16. The angle of departure of the root locus from a pole of $G(s)H(s)$:

$$\theta = 180° + \sum(angles\ to\ zeros) - \sum(angles\ to\ poles) \quad (25)$$

17. The angle of arrival at a zero:

$$\theta = 180° - \sum(angles\ to\ zeros) + \sum(angles\ to\ poles) \quad (26)$$

18. The steady-state error:

$$e_{ss} = \lim_{t\to\infty} e(t) = \lim_{s\to 0} sE(s) \quad (27)$$

where the error signal is given as:

$$E(s) = \frac{1}{1 + K(s)G(s)H(s)} \times U(s) \quad (28)$$

19. Linear system (SISO) with state feedback:

$$\dot{\boldsymbol{x}} = (\boldsymbol{A} - \boldsymbol{B}\boldsymbol{K}^T)\boldsymbol{x} + \boldsymbol{B}u$$

$$\text{or, } \dot{\boldsymbol{x}} = \boldsymbol{A}_{new}\boldsymbol{x} + \boldsymbol{B}u \quad (29)$$

where $\boldsymbol{A}_{new}$ is the augmented matrix and $u = \boldsymbol{K}^T\boldsymbol{x} + \delta_{ref}$

20. The characteristic equation for the standard form of the second-order differential equation:

$$\lambda^2 + 2\xi\omega_n\lambda + \omega_n^2 = 0$$

The roots of the characteristic equation are: (30)

$$\lambda_{1,2} = -\xi\omega_n \pm \omega_n\sqrt{1-\xi^2} \cdot i$$

$$\lambda_{1,2} = \sigma \pm \omega_d$$

21. The calculation of controller gains using the Ziegler-Nichols method:

Table 1 The Ziegler-Nichols tuning method.

Control Type	K_p	K_I	K_D
P	$0.5K_u$	-	-
PI	$0.45K_u$	$1.2\,K_p/T_u$	-
PD	$0.8K_u$	-	$K_PT_u/8$
Classic PID	$0.6K_u$	$2\,K_p/T_u$	$K_PT_u/8$
Pessen Integral Rule	$0.7K_u$	$2.5\,K_p/T_u$	$3K_PT_u/20$
Some Overshoot	$0.33K_u$	$2\,K_p/T_u$	$K_PT_u/3$
No Overshoot	$0.2K_u$	$2\,K_p/T_u$	$K_PT_u/3$

(31)

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22. The contribution of the wing-body to M_{cg}:

$$C_{M,cg_{wb}} = C_{M,ac_{wb}} + C_{L_{wb}}\left(h - h_{ac_{wb}}\right)$$

$$C_{M,cg_{wb}} = C_{M,ac_{wb}} + a_{wb}\alpha_{wb}\left(h - h_{ac_{wb}}\right) \quad (32)$$

23. The contribution of the wing-body-tail to M_{cg}:

$$C_{M,cg_{wb}} = C_{M,ac_{wb}} + a\alpha_a\left(h - h_{ac_{wb}} - V_H\frac{a_t}{a}\left[1 - \frac{\partial\varepsilon}{\partial\alpha}\right]\right) + V_H a_t(i_t + \varepsilon_0) \quad (33)$$

24. The equation for longitudinal static stability:

$$C_{M,0} = C_{M,ac_{wb}} + V_H a_t(i_t + \varepsilon_0)$$

$$\frac{\partial C_{M,cg}}{\partial\alpha_a} = a\left[h - h_{ac_{wb}} - V_H\frac{a_t}{a}\left(1 - \frac{\partial\varepsilon}{\partial\alpha}\right)\right] \quad (34)$$

25. The absolute angle of attack, α_a:

$$\alpha_a = \alpha + |\alpha_{L=0}| \quad (35)$$

where α is the geometric angle of attack.

26. Neutral point:

$$h_n = h_{ac_{wb}} + V_H\frac{a_t}{a}\left(1 - \frac{\partial\varepsilon}{\partial\alpha}\right) \quad (36)$$

27. Static margin:

$$SM = h_n - h \quad (37)$$

28. Elevator angle to trim:

$$\delta_{trim} = \frac{C_{M,0} + \left(\partial C_{M,cg}/\partial\alpha_a\right)\alpha_n}{V_H\left(\partial C_{L,t}/\partial\,\delta_e\right)} \quad (38)$$

29. Conversion from the state-space model to transfer function model: (39)

$$G(s) = \boldsymbol{C}\frac{adj(\boldsymbol{sI} - \boldsymbol{A})}{\det(\boldsymbol{sI} - \boldsymbol{A})}\boldsymbol{B}$$

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