Universiti Tun Hussein Onn Malaysia

UNIVERSITI TUN HUSSEIN ONN MALAYSIA

FINAL EXAMINATION
SEMESTER II
SESSION 2021/2022

COURSE NAME	:	ELECTROMECHANICAL AND CONTROL SYSTEM
COURSE CODE	:	BDU 20302
PROGRAMME CODE	:	BDC/BDM
EXAMINATION DATE	:	JULY 2022
DURATION	:	3 HOURS
INSTRUCTION	:	1. ANSWER **FOUR (4)** QUESTIONS **ONLY.** 2. THIS FINAL EXAMINATION IS CONDUCTED VIA **OPEN BOOK**.

THIS QUESTION PAPER CONSISTS OF **ELEVEN (11)** PAGES

Q1 Assume fuselage aerodynamics effects are neglected. At α = 2.6° the lift coefficient for the wing is measured as 0.48. The lift is found to be zero at a geometric angle of attack α = −1.1°. The moment coefficients about center of gravity for α = 1.3° and α = 4.8° are −0.01 and 0.05, respectively. The location of the center of gravity is 0.3.

(a) Calculate $C_{M,ac_{wb}}$ and location of the aerodynamic center of the wing. If lift due to the aerodynamic forces are neglected, examine the pitch direction of the wing.

(8 marks)

(b) Now assume that a horizontal tail is added to model with the characteristic of tail is shown in **Table Q1(b).** Compute the $C_{M,cg}$ at α = 4.8°. Analyze the stability of the aircraft as a whole in term of longitudinal mode.

(12 marks)

(c) If aircraft flying at steady state is pertubated with upward gust of wind. Compare the stability of an aircraft with respect to both moment coefficient curves illustrated in **Figure Q1(c).**

(5 marks)

Q2 (a) List the characteristics of the short period and phugoid stability modes.

(5 marks)

(b) Consider an aircraft model in a wind tunnel setup where the aircraft is constrained at its center of gravity. The aircraft is free to perform a pitching motion about its center of gravity. The governing equation of this simple motion is obtained from Newton's second law and is given as:

$$\Delta\ddot{\alpha} - (M_q + M_{\dot{\alpha}})\Delta\dot{\alpha} - M_\alpha \Delta\alpha = M_{\delta e}\Delta\delta_e$$

where $\Delta\alpha$ is the change in the angle of attack (Assumption: the change in the angle of attack and pitch angles are identical), $\Delta\delta e$ is the change in elevator angle. Derivatives, M_q and M_α are the longitudinal derivatives due to the pitching velocity and the angle of attack. Find the transfer function relating the change in the angle of attack, $\Delta\alpha(s)$ and the change in elevator angle $\Delta\delta e(s)$. Use the Laplace transform theorem in **Table Q2(b).**

(2 marks)

(c) Determine the solution, $\alpha(t)$ for the governing equation in **Question Q2(b)** if a step input is applied to the elevator using the following data:

$$M_q = -2.05\ s^{-1}$$
$$M_\alpha = -8.80\ s^{-2}$$
$$M_{\dot{\alpha}} = -0.95\ s^{-2}$$
$$M_{\delta e} = -5.5\ s^{-2}$$

Use partial fraction and inverse Laplace theorem to obtain the output response of the system, $\alpha(t)$ with the initial conditions of $\alpha(0) = 0$ and $\frac{d\alpha(0)}{dt} = 0$.

(14 marks)

(c) A rotorcraft based unmanned aerial vehicle (UAV) is installed in a test rig to test the functionality of the autopilot system. The UAV prototype is constrained so that it can only rotate about the z-axis (i.e., producing a pure yawing motion). The yaw angle to the rudder input transfer function can be modeled according to:

$$\frac{\psi(s)}{\delta_{rud}(s)} = \frac{10}{s^2 + 0.5s + 2}$$

Design a heading control system so that the model has the system can exhibit closed-loop performance with damping ratio, $\xi = 0.6$ and setting time, $t_s \leq 2.5$ s. Consider the sensor used in the control system design to be a perfect device.

(10 marks)

Q5 Consider the unity feedback system shown in **Figure Q5** with:

$$G(s) = \frac{K_p(s+6)}{(s+2)(s+3)(s+5)}$$

is operating with a damping ratio of 0.707.

(a) Design a PI controller to drive the step response error to zero and compare the specifications of the uncompensated and compensated system. Provide a detailed root locus plot for the closed-loop system as K_p 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.

(25 marks)

-END OF QUESTIONS-

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Table Q1(b): Aircraft with tail characteristics

Wing area	0.2 m^2
Wing chord	0.25 m
Distance C.g to A.c of tail	0.19 m
Tail area	0.04 m^2
Tail setting angle	3 degrees
Tail slope	0.2 /degree
Downwash angle	1 degree
$\partial\varepsilon/\partial\alpha$	0.4

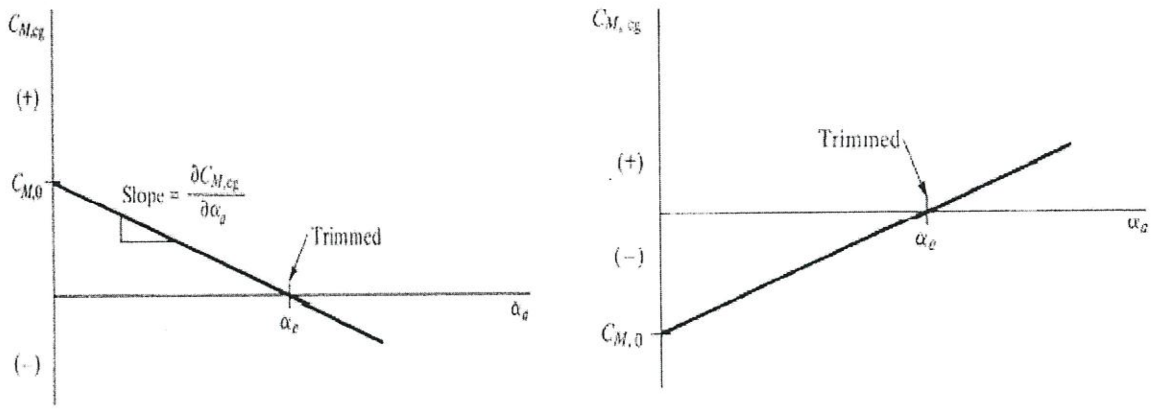

Figure Q1(c): Moment coefficient curves

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Table Q2(b) The Laplace transform theorems.

Laplace transforms – Table			
$f(t) = L^{-1}\{F(s)\}$	$F(s)$	$f(t) = L^{-1}\{F(s)\}$	$F(s)$
$a \quad t \geq 0$	$\frac{a}{s} \quad s > 0$	$\sin \omega t$	$\frac{\omega}{s^2 + \omega^2}$
$at \quad t \geq 0$	$\frac{a}{s^2}$	$\cos \omega t$	$\frac{s}{s^2 + \omega^2}$
e^{-at}	$\frac{1}{s+a}$	$\sin(\omega t + \theta)$	$\frac{s \sin \theta + \omega \cos \theta}{s^2 + \omega^2}$
te^{-at}	$\frac{1}{(s+a)^2}$	$\cos(\omega t + \theta)$	$\frac{s \cos \theta - \omega \sin \theta}{s^2 + \omega^2}$
$\frac{1}{2}t^2 e^{-at}$	$\frac{1}{(s+a)^3}$	$t \sin \omega t$	$\frac{2\omega s}{(s^2 + \omega^2)^2}$
$\frac{1}{(n-1)!}t^{n-1}e^{-at}$	$\frac{1}{(s+a)^n}$	$t \cos \omega t$	$\frac{s^2 - \omega^2}{(s^2 + \omega^2)^2}$
e^{at}	$\frac{1}{s-a} \quad s > a$	$\sinh \omega t$	$\frac{\omega}{s^2 - \omega^2} \quad s > \lvert\omega\rvert$
te^{at}	$\frac{1}{(s-a)^2}$	$\cosh \omega t$	$\frac{s}{s^2 - \omega^2} \quad s > \lvert\omega\rvert$
$\frac{1}{b-a}(e^{-at} - e^{-bt})$	$\frac{1}{(s+a)(s+b)}$	$e^{-at} \sin \omega t$	$\frac{\omega}{(s+a)^2 + \omega^2}$
$\frac{1}{a^2}[1 - e^{-at}(1 + at)]$	$\frac{1}{s(s+a)^2}$	$e^{-at} \cos \omega t$	$\frac{s+a}{(s+a)^2 + \omega^2}$
t^n	$\frac{n!}{s^{n+1}} \quad n = 1,2,3..$	$e^{at} \sin \omega t$	$\frac{\omega}{(s-a)^2 + \omega^2}$
$t^n e^{at}$	$\frac{n!}{(s-a)^{n+1}} \quad s > a$	$e^{at} \cos \omega t$	$\frac{s-a}{(s-a)^2 + \omega^2}$
$t^n e^{-at}$	$\frac{n!}{(s+a)^{n+1}} \quad s > a$	$1 - e^{-at}$	$\frac{a}{s(s+a)}$
$\sqrt{t}$	$\frac{\sqrt{\pi}}{2s^{3/2}}$	$\frac{1}{a^2}(at - 1 + e^{-at})$	$\frac{1}{s^2(s+a)}$
$\frac{1}{\sqrt{t}}$	$\sqrt{\frac{\pi}{s}} \quad s > 0$	$f(t - t_1)$	$e^{-t_1 s}F(s)$
$g(t) \cdot p(t)$	$G(s) \cdot P(s)$	$f_1(t) \pm f_2(t)$	$F_1(s) \pm F_2(s)$
$\int f(t)dt$	$\frac{F(s)}{s} + \frac{f^{-1}(0)}{s}$	$\delta(t)$ *unit impulse*	$1 \quad$ *all s*
$\frac{df}{dt}$	$sF(s) - f(0)$	$\frac{d^2 f}{df^2}$	$s^2F(s) - sf(0) - f'(0)$
$\frac{d^n f}{dt^n}$	$s^nF(s) - s^{n-1}f(0) - s^{n-2}f'(0) - s^{n-3}f''(0) - \cdots - f^{n-1}(0)$		

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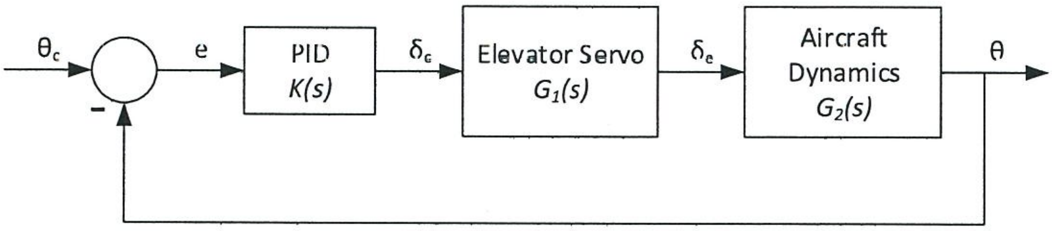

Figure Q3 Simplified block diagram for pitch angle control system.

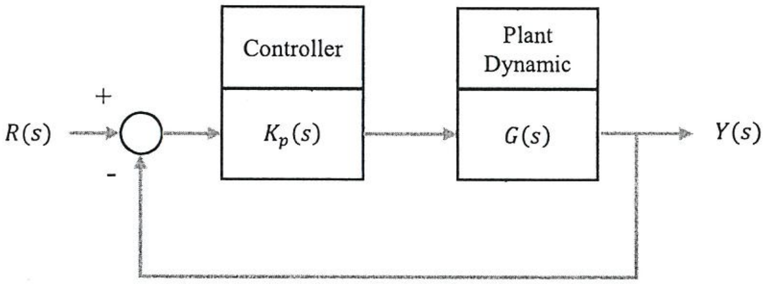

Figure Q5 The uncompensated system.

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A 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:

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

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

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. (31)

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	$0.2K_u$	$2\,K_p/T_u$	$K_pT_u/3$

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

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

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:

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