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UNIVERSITI TUN HUSSEIN ONN MALAYSIA

FINAL EXAMINATION
SEMESTER I
SESSION 2018/2019

COURSE NAME	:	ELECTROMECHANICAL AND CONTROL
COURSE CODE	:	BDU 20302
PROGRAMME	:	BDC/BDM
EXAMINATION DATE	:	DECEMBER 2018/JANUARY 2019
DURATION	:	2 HOURS 30 MINUTES
INSTRUCTION	:	ANSWER **FOUR (4)** QUESTIONS **ONLY**

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

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Q1 (a) Give the definition of static stability and list the necessary criteria for longitudinal balance and static stability.

(2 marks)

(b) Consider a wing-body shaped model mounted in a test section of a low-speed wind tunnel. The flow conditions in the test section are assumed to be at standard sea level properties. The wing-body model is tested with an airflow velocity of 100 m/s. The wing area and chord are 1.5 m^2 and 0.45 m, respectively. Using the wind tunnel force and moment measuring balance, the moment about the center of gravity when the lift force measurement is zero is found to be -12.4 Nm. When the model is pitched to another angle of attack, the lift and moment about the center of gravity are measured to be 3675 N and 20.67 Nm, respectively. Calculate the value of the moment coefficient about the aerodynamic center and deteremine the location of the aerodynamic center.

(4 marks)

(c) Assume that a horizontal tail with no elevator is added to the wing-body model in **Question Q1(b)**. The distance from the aircraft's center of gravity to the tail's aerodynamic center is 1.2 m. The area of the tail is 0.5 m^2 and the tail setting angle is 2.1°. The lift slope of the tail is 0.15 per degree. From experimental measurement, $\varepsilon_0 = 0$, and $\partial\varepsilon/\partial\alpha = 0.45$. If the absolute angle of attack of the model is 5° and the lift at this angle of attack is 4135 N, calculate the moment about the center of gravity.

(6 marks)

(d) Consider the wing-body-tail model in **Question Q1(c).** Does this model have longitudinal static stability and balance? Determine the trimmed angle of attack, the neutral point and the static margin for the wing-body-tail model. Assume that the location of the center of gravity is at $h = 0.3$.

(10 marks)

(e) Assume that an elevator is added to the horizontal tail of the configuration given in **Question Q1(c).** The elevator control effectiveness is 0.05. Calculate the elevator deflection angle necessary to trim the configuration at an angle of 6°.

(3 marks)

Q2 (a) The roll mode approximation and aerodynamic data for the Douglas DC-8 aircraft at cruising ($M = 0.44$) are given as follows:

$$\begin{bmatrix} \dot{p} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} -1.232 & 0 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} p \\ \phi \end{bmatrix} + \begin{bmatrix} -1.62 & 0.392 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_{ail} \\ \delta_{rud} \end{bmatrix}$$

Find the solution to the given state space model using Paynter's numerical method. Use time interval, $\Delta t = 0.1$ to solve the numerical problem.

(16 marks)

(b) If the input of the system is applied with 1° aileron step input and the following output equation and initial condition are used:

$$\phi_k = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} p_k \\ \phi_k \end{bmatrix} \qquad \begin{bmatrix} p_0 \\ \phi_0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

Determine the output response, ϕ_k of the state equation up to 3 iterations.

(9 marks)

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

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

$$G_1(s) = \frac{10}{s+10}$$

$$G_2(s) = \frac{3}{s^2+3s+4}$$

(a) Examine the locus movement of the open loop transfer function in a root locus plot and find the damped frequency, ω_d and gain, K, values at the imaginary axis crossing if such a situation exists.

(10 marks)

(b) Design the automatic controllers (i.e. P, PD, and PID control) for the dynamic system under consideration using the Ziegler and Nichols tuning method.

(8 marks)

(c) Compare the steady-state error performance of the compensated systems (i.e. P, PD, and PID control). Describe any problems with your design.

(7 marks)

Q4 The open loop pitch rate response to elevator transfer function for the Lockheed F-104 Starfighter is given by the following transfer function:

$$\frac{q(s)}{\delta_e(s)} = \frac{-4.66s(s+0.133)(s+0.269)}{(s^2+0.015s+0.021)(s^2+0.911s+4.884)}$$

The root locus plot of the transfer function is given in **Figure Q4**.

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

(4 marks)

(b) Determine the damping ratio and undamped natural frequency for short period and phugoid mode.

(4 marks)

(c) Design a pitch rate feedback controller, K_q to bring the closed loop short period mode in agreement with the minimum specification for damping ratio and natural frequency. Assume the following Level 1 flying qualities are used in the analysis:

Phugoid damping ratio $\zeta_p \geq 0.04$

Short period damping ratio $\zeta_s \geq 0.5$

Short period undamped natural frequency $0.8 \leq \omega_s \leq 3.0$ rad/s

(11 marks)

(d) Compare the augmented short period damping ratio and the natural frequency with those of the unaugmented aircraft. Examine the effect of pitch rate feedback that was used to improve the longitudinal flying qualities. Explain your answer based on your findings and the given root locus plot.

(6 marks)

Q5 The Wright Flyer was known to be a statically and dynamically unstable aircraft. However, the Wright brothers were able to fly their aircraft successfully due to sufficient control authority incorporated into their aircraft design. Although the airplane was difficult to fly, the combination of the pilot and aircraft could be a stable system (see **Figure Q5**). If the closed loop pilot is represented as a pure gain, K_p, and the pitch attitude to canard deflection is given as follows:

$$G_2(s) = \frac{K_p(s+0.5)(s+3)}{(s^2+0.72s+1.44)(s^2+5.9s-11.9)}$$

(a) Determine the centroid and asymptotes angle of the root locus plot of the closed-loop system.

(6 marks)

(b) Calculate the angle of departure from the complex poles.

(6 marks)

(c) Draw the root locus for the closed-loop system.

(8 marks)

(d) Determine the range of pilot gain, K_p for which the system is stable.

(5 marks)

-END OF QUESTION-

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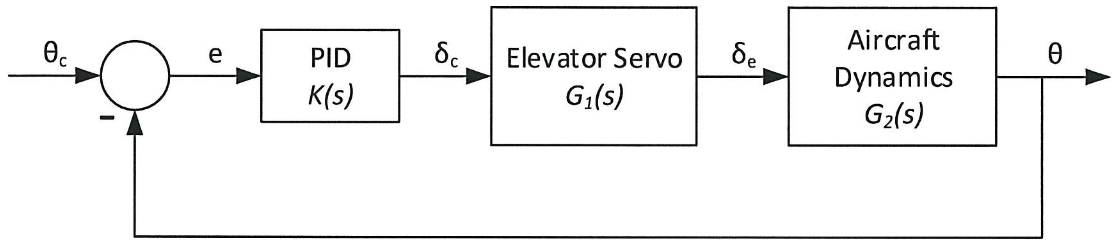

Figure Q3 Simplified block diagram for pitch angle control system.

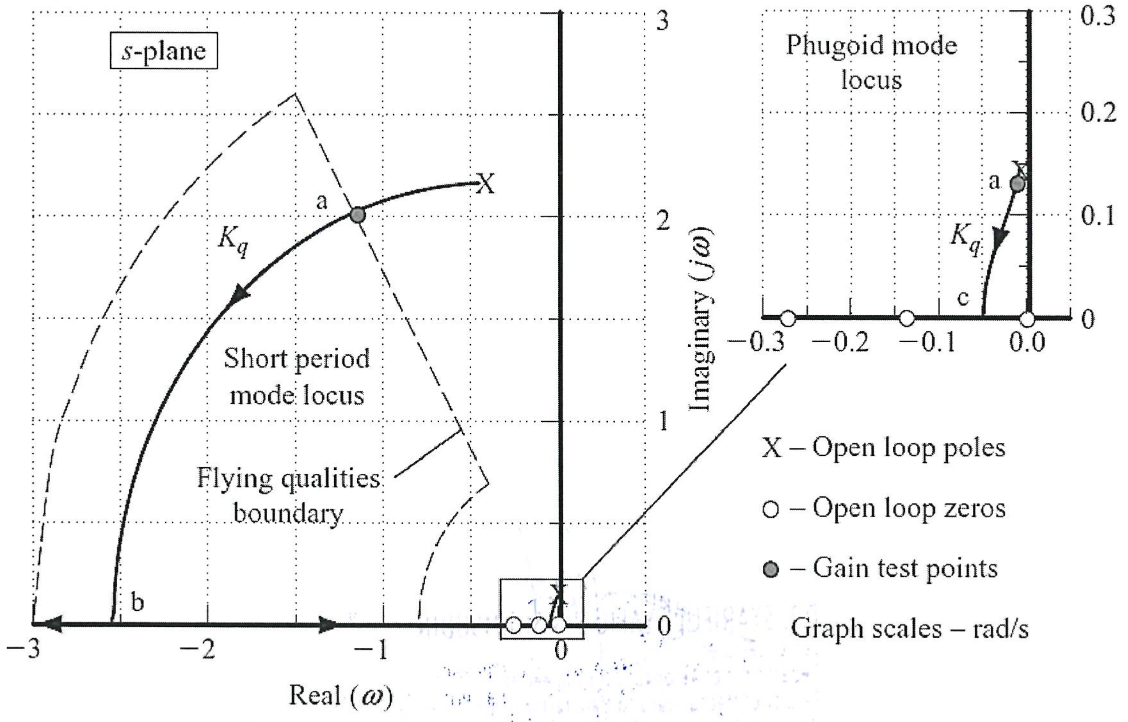

Figure Q4 Root locus plot showing pitch rate feedback to the elevator.

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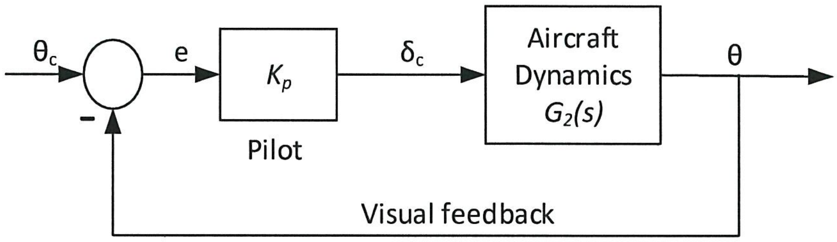

Figure Q5 Block diagram for the Wright Flyer control system.

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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)

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

10. Estimation of 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:

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

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

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. Solution to find 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 controller gains calculation using the Ziegler-Nichols method: (31)

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

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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. 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:

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

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