ENG11

# UNIVERSITY OF BOLTON

# SCHOOL OF ENGINEERING

# BEng (Hons) MECHANICAL ENGINEERING

# SEMESTER ONE EXAMINATION 2024/25

# ADVANCED THEMOFLUID & CONTROL SYSTEMS

# MODULE NO: AME6015

**Date: Friday 10th January 2025** **Time: 10:00 – 12:00**

---

**INSTRUCTIONS TO CANDIDATES:**

**There are SIX questions.**

**Answer ANY FOUR questions.**

**All questions carry equal marks.**

**Marks for parts of questions are shown in brackets.**

**This examination paper carries a total of 100 marks.**

**All working must be shown. A numerical solution to a question obtained by programming an electronic calculator will not be accepted.**

---

School of Engineering
BEng Mechanical Engineering
Semester One Examination 2024/25
Advanced Thermofluids and Control Systems
Module No: AME6015

**QUESTION 1**

The landing craft suspension System and free body diagram at a landing operation is shown in Figure Q1.

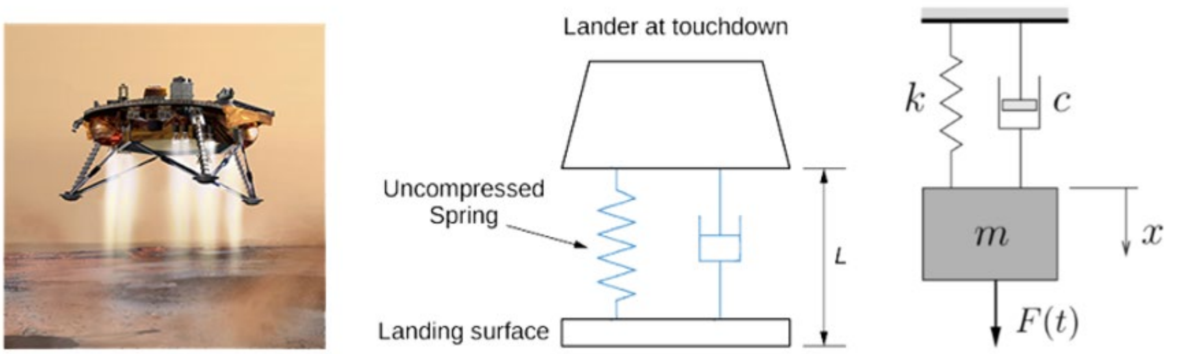



***Figure Q1 The landing craft suspension System***

(a) Derive the differential equations describing the behaviour of the system in Figure Q1 giving the relationship between the input force and the output of displacement x.

**[6 Marks]**

(b) Write out the transfer function expression for this system using Laplace transform if m =5kg, c = 35Ns/m, k=350N/m, force F(t) = 300F(t) and assuming zero initial condition.

**[7 Marks]**

(c) State the number of poles and zeros in the system. Give reasons for your answer.

**[4 Marks]**

(d) Check for if the system is controllable and observable.

**[8 Marks]**

**Total 25 marks**

**QUESTION 2**

A PID controller is used to control a servo control system as shown in **Figure Q2.** The open loop transfer function of the plant is given by

$$G_p(s) = \frac{60}{(s+2)(s+5)}$$

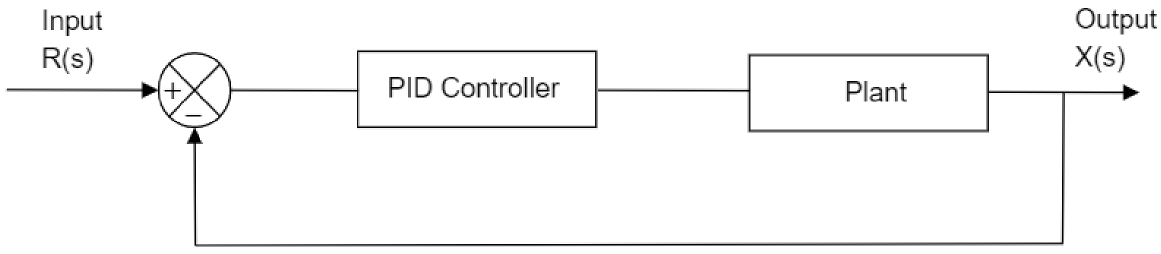



***Figure Q2: Control system of the processing plant.***

a) Evaluate the performances of closed loop servo control system (natural frequency, damping ratio, Percentage Overshoot, peak time, rise time, settling time and steady-state error) to assess its performance without the PID controller.

**(10marks)**

b) Design a PD controller to determine the parameter $K_p$ and $K_d$, and clearly identify the design procedure if the system responses for a unit step input are required as:

- The maximum overshoot is less than 8%.
- The settling time is 55% less than that of without the PD controller.

**(15 marks)**

**Total 25 marks**

**PLEASE TURN THE PAGE**

**QUESTION 3**

Why is it necessary to use a Digital-to-Analog Converter in a control system with digital controllers and analog actuators? **[5 Marks]**

b) If a Pneumatic control system as shown in Figure Q3 (a) shows the system consists of a Digital to Analogue Converter with a zero-order hold element in series with the Pneumatic control which has a transfer function;

$$G(s) = \frac{8}{s(s+2)}$$

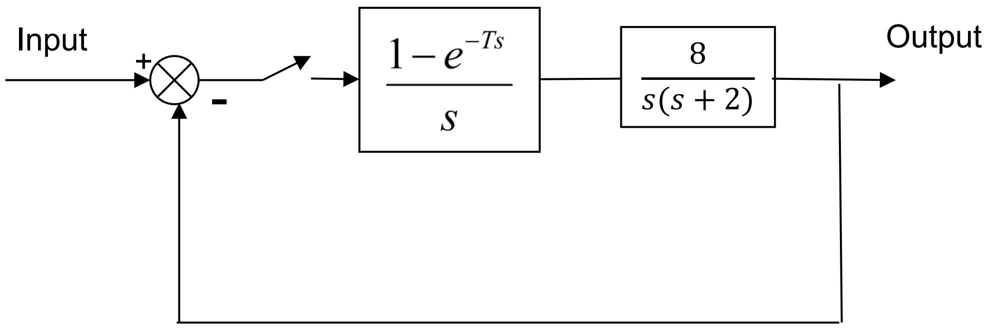



**Figure Q3 (a) A Pneumatic control system**

I. Find the sampled-data transfer function, G(z) for the digital control system. The sampling time, T, is 0.45 seconds. **[8 Marks]**

II. What is the resolution of the AD converter? **[3 Marks]**

III. What integer number represented a value of 8 Volts? **[3 Marks]**

IV. What voltage does the integer 150 represent? **[3 Marks]**

V. What voltage does 10101101 represent? **[3 Marks]**

**Total 25 marks**

**QUESTION 4**

A horizontal pipe with an internal diameter of 0.02 meters and a length of 10 metres carries water at a steady velocity of 0.01 m/s as shown in **Figure 4**. The water has a density (ρ) of 1000 kg/m³ and a dynamic viscosity (μ) of 0.001 kg/m-s. A Computational Fluid Dynamics (CFD) simulation predicts a pressure difference of 7.73 Pa between the inlet and outlet of the pipe.

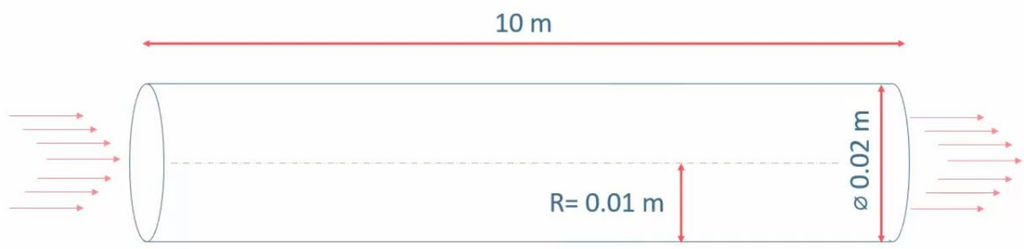



***Figure 4 Flow through Pipe***

a. Based on the given data calculate the Reynolds number for the flow and determine whether the flow is laminar or turbulent.

**[3 Marks]**

b. Select the appropriate formula for calculating the friction factor for the flow and determine the head loss in metres.

**[7 Marks]**

c. Calculate the pressure difference analytically and compare this analytical pressure difference with the CFD result. Moreover, calculate the percentage error between the analytical and CFD pressure differences.

**[10 Marks]**

d. Explain the three main steps involved in a typical Computational Fluid Dynamics (CFD) simulation.

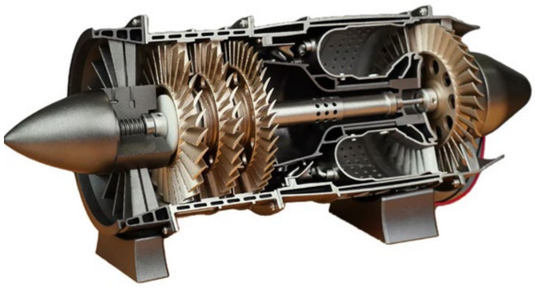
**[5 Marks]**

**Total 25 marks**
**PLEASE TURN THE PAGE**

School of Engineering
BEng Mechanical Engineering
Semester One Examination 2024/25
Advanced Thermofluids and Control Systems
Module No: AME6015

**QUESTION 5**

A military jet, designed for supersonic speeds, is cruising at Mach 2 (approximately 680 m/s) at an altitude where the air density is 0.2 kg/m³. The jet is powered by two turbojet engines, each with an air intake of 50 kg/s and an exhaust velocity of 1,200 m/s relative to the jet. This supersonic jet's propulsion relies on the principles of thrust generated by accelerating a mass of air backward. For the purposes of this calculation, assume steady-level flight with no significant altitude changes. Your task is to provide the following information based on the given scenario:



a) Calculate the thrust produced by one engine.

**[5 Marks]**

b) Determine the total thrust produced by both engines.

**[4 Marks]**

c) Estimate the fuel consumption if each engine has a specific fuel consumption (SFC) of 0.8 kg/(N·hr).

**[8 Marks]**

d) What are the basic principles of jet propulsion, and how does Newton's Third Law of Motion apply to it?

**[8 Marks]**

**Total 25 marks**
**PLEASE TURN THE PAGE**

**QUESTION 6**

A jet aircraft is powered by a turbojet engine that needs to produce a thrust of 30,000 N to maintain a cruising speed of 250 m/s. The engine operates by accelerating the incoming air to an exhaust velocity of 800 m/s relative to the jet. Your task is to provide the following information based on the given scenario:

a) Calculate the mass flow rate of air required to achieve this thrust.

**[10 Marks]**

b) Calculate the propulsive efficiency of the engine.

**[10 Marks]**

c) If jet engine has a propulsive power of 6 MW and a total energy input rate of 15 MW (based on fuel combustion). Calculate the thermal efficiency of the engine

**[5 Marks]**

**Total 25 marks**

**END OF QUESTIONS**

**PLEASE TURN PAGE FOR FORMULA SHEET**

## <u>Formula Sheet</u>

### Blocks with feedback loop

G(s) = $\dfrac{Go(s)}{1+Go(s)H(s)}$ (for a negative feedback)

G(s) = $\dfrac{Go(s)}{1-Go(s)H(s)}$ (for a positive feedback)

### Steady-State Errors

$e_{ss} = \lim_{s\to 0}[s(1-G_O(s))\theta_i(s)]$ (for an open-loop system)

$e_{ss} = \lim_{s\to 0}[s\dfrac{1}{1+G_o(s)}\theta_i(s)]$ (for the closed-loop system with a unity feedback)

$e_{ss} = \lim_{s\to 0}[s\dfrac{1}{1+\dfrac{G_0(s)}{1+G_0(s)[H(s)-1]}}\theta_i(s)]$ (if the feedback H(s) ≠ 1)

$e_{ss} = \lim_{s\to 0}[-s\cdot\dfrac{G_2(s)}{1+G_2(s)G_1(s)}\cdot\theta_d]$ (if the system subjects to a disturbance input)

$$\text{state} - \text{space matrices for a second} - \text{order system } \frac{bo}{(s^2+a1s+ao)}$$

$$\frac{{\omega_n}^2}{s^2+2\beth\omega_n s+{\omega_n}^2}$$

### Laplace Transforms

A unit impulse function 1

A unit step function $\dfrac{1}{s}$

A unit ramp function $\dfrac{1}{s^2}$

### First order Systems

$$G(s) = \frac{\theta_o}{\theta_i} = \frac{G_{ss}(s)}{\tau s + 1}$$

$$\tau\left(\frac{d\theta_o}{dt}\right) + \theta_o = G_{ss}\theta_i$$

$\theta_O = G_{ss}(1 - e^{-t/\tau})$ (for a unit step input)

$\theta_O = AG_{ss}(1 - e^{-t/\tau})$ (for a step input with size A)

$\theta_o(t) = G_{ss}(\frac{1}{\tau})e^{-(t/\tau)}$ (for an impulse input)

**Second-order systems**

$$\frac{d^2\theta_o}{dt^2} + 2\zeta\omega_n\frac{d\theta_o}{dt} + \omega_n^2\theta_o = b_o\omega_n^2\theta_i$$

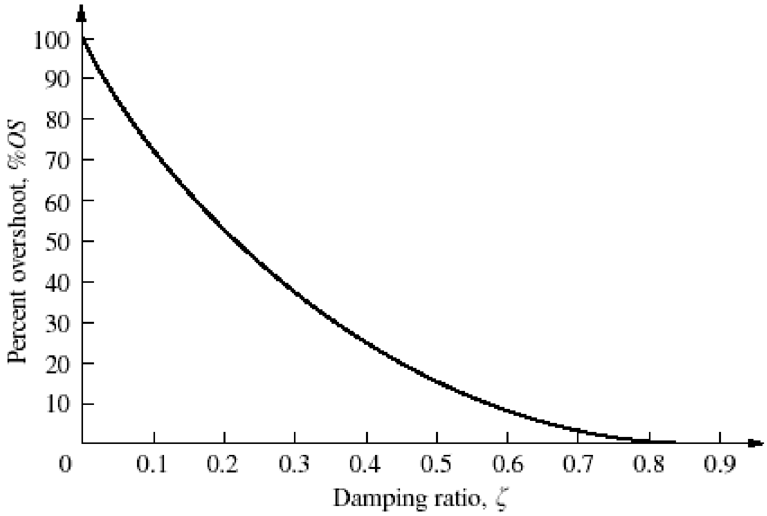
$$G(s) = \frac{\theta_o(s)}{\theta_i(s)} = \frac{b_o\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

$\omega_d t_r = 1/2\pi$ $\omega_d t_p = \pi$

P.O. = $\exp\left(\frac{-\zeta\pi}{\sqrt{(1-\zeta^2)}}\right) \times 100\%$

$t_s = \frac{4}{\zeta\omega_n}$ $\omega_d = \omega_n\sqrt{(1-\zeta^2)}$

**PLEASE TURN PAGE**




$$h_f = \frac{\Delta P}{\rho g}$$

$$h_f = \frac{4fLV^2}{2gD}$$

$$f = \frac{16}{R_e}$$

$$f = \frac{0.079}{{R_e}^{0.25}}$$

$$F = \dot{m} \times (V_{\text{exit}} - V_{\text{jet}})$$

$$\eta_{\text{propulsive}} = \frac{2v_0}{v_0 + v_e}$$

**Table 4.1** Laplace transforms

| *Laplace transform* | *Time function* | *Description of time function* |
|---|---|---|
| $1$ | | A unit impulse |
| $\frac{1}{s}$ | | A unit step function |
| $\frac{e^{-st}}{s}$ | | A delayed unit step function |
| $\frac{1-e^{-st}}{s}$ | | A rectangular pulse of duration $T$ |
| $\frac{1}{s^2}$ | $t$ | A unit slope ramp function |
| $\frac{1}{s^3}$ | $\frac{t^2}{2}$ | |
| $\frac{1}{s+a}$ | $e^{-at}$ | Exponential decay |
| $\frac{1}{(s+a)^2}$ | $te^{-at}$ | |
| $\frac{2}{(s+a)^3}$ | $t^2e^{-at}$ | |
| $\frac{a}{s(s+a)}$ | $1-e^{-at}$ | Exponential growth |
| $\frac{a}{s^2(s+a)}$ | $t-\frac{(1-e^{-at})}{a}$ | |
| $\frac{a^2}{s(s+a)^2}$ | $1-e^{-at}-ate^{-at}$ | |
| $\frac{s}{(s+a)^2}$ | $(1-at)e^{-at}$ | |
| $\frac{1}{(s+a)(s+b)}$ | $\frac{e^{-at}-e^{-bt}}{b-a}$ | |
| $\frac{ab}{s(s+a)(s+b)}$ | $1-\frac{b}{b-a}e^{-at}+\frac{a}{b-a}e^{-bt}$ | |
| $\frac{1}{(s+a)(s+b)(s+c)}$ | $\frac{e^{-at}}{(b-a)(c-a)}+\frac{e^{-bt}}{(c-a)(a-b)}+\frac{e^{-ct}}{(a-c)(b-c)}$ | |
| $\frac{\omega}{s^2+\omega^2}$ | $\sin \omega t$ | Sine wave |
| $\frac{s}{s^2+\omega^2}$ | $\cos \omega t$ | Cosine wave |
| $\frac{\omega}{(s+a)^2+\omega^2}$ | $e^{-at}\sin \omega t$ | Damped sine wave |
| $\frac{s+a}{(s+a)^2+\omega^2}$ | $e^{-at}\cos \omega t$ | Damped cosine wave |
| $\frac{\omega^2}{s(s^2+\omega^2)}$ | $1-\cos \omega t$ | |
| $\frac{\omega^2}{s^2+2\zeta\omega s+\omega^2}$ | $\frac{\omega}{\sqrt{(1-\zeta^2)}}e^{-\zeta\omega t}\sin[\omega\sqrt{(1-\zeta^2)}t]$ | |
| $\frac{\omega^2}{s(s^2+2\zeta\omega s+\omega^2)}$ with $\zeta < 1$ | $1-\frac{1}{\sqrt{(1-\zeta^2)}}e^{-\zeta\omega t}\sin[\omega\sqrt{(1-\zeta^2)}t+\phi]$ with $\zeta = \cos\phi$ | |

**Table 15.1** $z$-transforms

| *Sampled $f(t)$, sampling period $T$* | $F(z)$ |
|---|---|
| Unit impulse, $\delta(t)$ | $1$ |
| Unit impulse delayed by $kT$ | $z^{-k}$ |
| Unit step, $u(t)$ | $\frac{z}{z-1}$ |
| Unit step delayed by $kT$ | $\frac{z}{z^k(z-1)}$ |
| Unit ramp, $t$ | $\frac{Tz}{(z-1)^2}$ |
| $t^2$ | $\frac{T^2 z(z+1)}{(z-1)^3}$ |
| $e^{-at}$ | $\frac{z}{z-e^{-aT}}$ |
| $1-e^{-at}$ | $\frac{z(1-e^{-aT})}{(z-1)(z-e^{-aT})}$ |
| $t\,e^{-at}$ | $\frac{Tz\,e^{-aT}}{(z-e^{-aT})^2}$ |
| $e^{-at}-e^{-bt}$ | $\frac{(e^{-aT}-e^{-bT})z}{(z-e^{-aT})(z-e^{-bT})}$ |
| $\sin\omega t$ | $\frac{z\sin\omega T}{z^2-2z\cos\omega T+1}$ |
| $\cos\omega t$ | $\frac{z(z-\cos\omega T)}{z^2-2z\cos\omega T+1}$ |
| $e^{-at}\sin\omega t$ | $\frac{z\,e^{-aT}\sin\omega T}{z^2-2z\,e^{-aT}\cos\omega T+e^{-2}}$ |
| $e^{-at}\cos\omega t$ | $\frac{z(z-e^{-aT}\cos\omega T)}{z^2-2z\,e^{-aT}\cos\omega T+e^{-2}}$ |

**Table 15.2** $z$-transforms

| $f[k]$ | $f[0], f[1], f[2], f[3], \ldots$ | $F(z)$ |
|---|---|---|
| $1u[k]$ | $1, 1, 1, 1, \ldots$ | $\frac{z}{z-1}$ |
| $a^k$ | $a^0, a^1, a^2, a^3, \ldots$ | $\frac{z}{z-a}$ |
| $k$ | $0, 1, 2, 3, \ldots$ | $\frac{z}{(z-1)^2}$ |
| $ka^k$ | $0, a^1, 2a^2, 3a^3, \ldots$ | $\frac{az}{(z-a)^2}$ |
| $ka^{k-1}$ | $0, a^0, 2a^1, 3a^2, \ldots$ | $\frac{z^2}{(z-a)^2}$ |
| $e^{-ak}$ | $e^0, e^{-a}, e^{-2a}, e^{-3a}, \ldots$ | $\frac{z}{z-e^{-a}}$ |

**END OF PAPER**