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UNIVERSITI SAINS MALAYSIA

Second Semester Examination  
2009/2010 Academic Session

April/May 2010

**EKC 462 – Advanced Process Control For Industrial Processes**  
***[Sistem Kawalan Lanjutan untuk Proses Industri]***

Duration : 3 hours  
*[Masa : 3 jam]*

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Please ensure that this examination paper contains EIGHT printed pages and ONE printed page of Appendix before you begin the examination.

*[Sila pastikan bahawa kertas peperiksaan ini mengandungi LAPAN muka surat yang bercetak dan SATU muka surat Lampiran sebelum anda memulakan peperiksaan ini.]*

**Instruction:** Answer **ALL** questions.

**Arahan:** Jawab **SEMUA** soalan.]

In the event of any discrepancies, the English version shall be used.

*[Sekiranya terdapat sebarang percanggahan pada soalan peperiksaan, versi Bahasa Inggeris hendaklah digunapakai].*

Answer ALL questions.

Jawab SEMUA soalan.

1. [a] Explain the following:  
*Terangkan perkara-perkara yang berikut:*

[i] Nonlinear Control  
*Kawalan Tak Lelurus*

[ii] Adaptive Control  
*Kawalan Suai*

[iii] Model Based Control  
*Kawalan Berasaskan Model*

[6 marks/markah]

[b] What is an inferential control and give examples where it is required in chemical process control?

*Apakah kawalan taahir dan berikan contoh-contoh di mana ia diperlukan dalam kawalan proses kimia?*

[4 marks/markah]

[c] Design an IMC controller for each of the following process model using simple factorization. Keep your final answer in  $s$  domain.

*Rekabentukkan pengawal IMC bagi setiap proses model berikut dengan menggunakan pemfaktoran mudah. Kekalkan jawapan akhir anda dalam domain  $s$ .*

[i] 
$$\frac{s^2 - s - 2}{s^4 + 6.5s^3 + 15s^2 + 14s + 4}$$

[ii] 
$$\frac{10(s-1)e^{-s}}{s^2 + s - 2}$$

[iii] 
$$\frac{d^2 y}{dt^2} - 2\frac{dy}{dt} - 3y(t) = u(t) - \frac{d}{dt}u(t)$$

[15 marks/markah]

2. [a] Define the following terms:  
*Takrifkan terma-terma berikut:*

[i] Simple factorization  
*Pemfaktoran mudah*

[ii] All pass factorization  
*Pemfaktoran semua lulus*

[iii] Minimum phase  
*Fasa minimum*

[iv] Nonminimum phase  
*Fasa tak minimum*

[4 marks/markah]

[b] Derive a closed loop transfer function,  $Y/Y_{sp}$  for the Smith predictor when  $G_p(s) \neq \tilde{G}_p(s)$ . What is the characteristic equation?

*Terbitkan rangkap pindah gelung tertutup,  $Y/Y_{sp}$  bagi peramal Smith bila  $G_p(s) \neq \tilde{G}_p(s)$ . Apakah persamaan cirinya?*

[6 marks/markah]

[c] A reactor has the following input-output model, for control of output temperature ( $^{\circ}\text{C}$ ) by manipulating the jacket temperature ( $^{\circ}\text{C}$ ). The timescale is minutes.

*Sebuah reaktor mempunyai model masukan-keluaran berikut, untuk kawalan suhu keluaran ( $^{\circ}\text{C}$ ) dengan mengolah suhu jaket ( $^{\circ}\text{C}$ ). Skala masa ialah minit.*

$$\tilde{g}_p(s) = \frac{-2.5}{(10s + 1)(2s + 1)}$$

[i] Design the IMC-based PID controller for this system; that is, find  $K_c$ ,  $\tau_I$  and  $\tau_D$ . Show units for all parameters.

*Rekabentukkan pengawal PID berasaskan IMC bagi sistem ini; iaitu, cari  $K_c$ ,  $\tau_I$  dan  $\tau_D$ . Nyatakan unit bagi setiap parameter tersebut.*

[ii] What is the closed-loop transfer function? Sketch the expected response for a step setpoint change.

*Apakah rangkap pindah gelung tertutup bagi sistem ini? Lakarkan sambutan yang dijangkakan bagi satu perubahan langkah titik set.*

[15 marks/markah]

3. [a] What is it meant by prediction horizon (M) and control horizon (P) in model predictive control (MPC) schemes?

*Apakah yang dimaksudkan dengan ufuk ramalan (M) dan ufuk kawalan (P) dalam skema kawalan ramalan model (MPC)?*

*[2 marks/markah]*

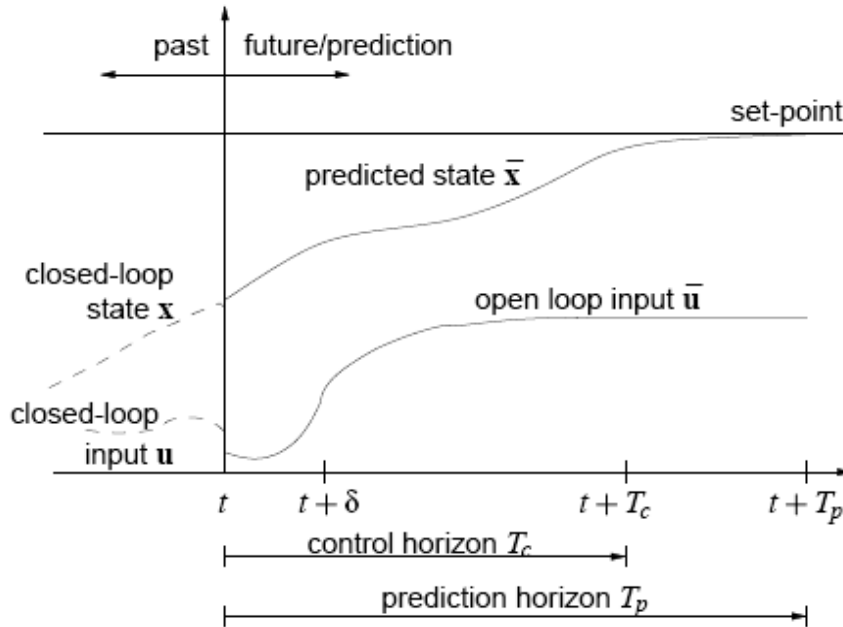


Figure Q.3.[b]: Principle of model predictive control.  
*Rajah S.3.[b]: Prinsip model kawalan ramalan*

- [b] Briefly explain the principle of MPC schemes based on the Figure Q.3.[b]?  
*Terangkan dengan ringkas prinsip skema MPC berdasarkan Rajah S.3.[b]?*

*[4 marks/markah]*

[c] Figure Q.3.[c] shows the schematic diagram of instrumentation associated with a bioreactor. The steam sterilization system and all sensors and transmitters are omitted for clarity.

*Rajah S.3.[c] menunjukkan rajah instrumentasi yang bersekutu dengan bioreaktor. Sistem steril stim, semua alat pengesan dan pengantar telah dikeluarkan untuk tujuan kejelasan.*

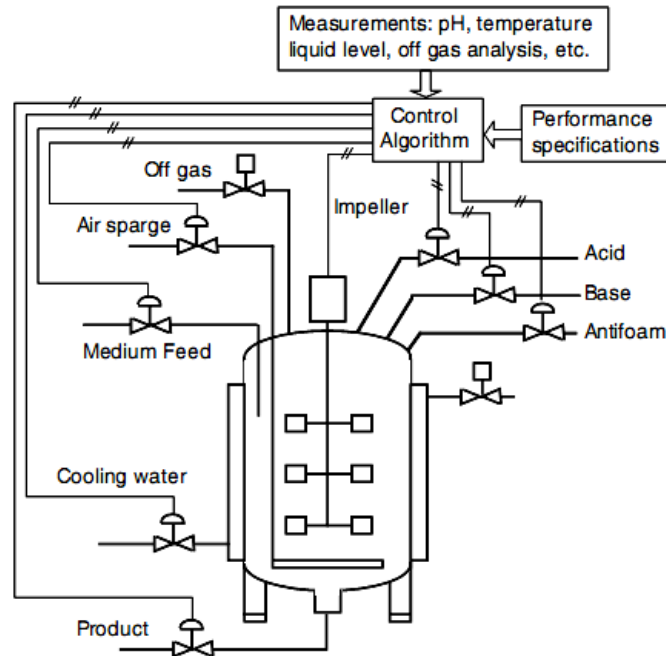


Figure Q.3.[c]. Bioreactor  
*Rajah S.3.[c]. Bioreaktor*

In this bioreactor the variables such as temperature, pH, dissolved oxygen, liquid level, feedflow rate, and the rotation speed of the impeller need to be monitored and controlled. In some operations, the biomass and the concentration of a specific chemical component in the liquid or the composition of the gas effluent were also need to be measured. In addition, the pressure, the temperature and the foam head also need to be monitored to make sure it does not become too high or too low. In short, the bioreactor needs to operate at the desired conditions. Therefore:

*Di dalam bioreaktor ini pembolehubah seperti suhu, pH, oksigen terlarut, aras cecair, aliran kemasukan dan kelajuan putaran pemutar hendaklah dipantau dan dikawal. Dalam sesetengah operasi, kepekatan biojisim dan juga kepekatan bahan kimia yang lain di dalam cecair mahupun komposisi gas efluen perlu diukur. Sebagai tambahan, tekanan, suhu dan ketinggian buih juga perlu dilihat untuk memastikan ianya tidak terlalu tinggi atau terlalu rendah. Secara ringkasnya, bioreaktor ini perlu beroperasi dalam keadaan yang diinginkan. Oleh itu,*

- [i] Outlines and explain on how MPC strategy can be applied for this bioreactor (this should include all the steps involved in implementing MPC until commissioning of the bioreactor).

*Gariskan dan terangkan bagaimana strategi MPC boleh digunakan untuk bioreaktor ini (ini termasuklah semua langkah yang terlibat dalam melaksanakan MPC sehinggalah pelancaran bioreaktor tersebut).*

*[15 marks/markah]*

- [ii] Comments the advantages and disadvantages of MPC application related to this bioreactor control strategy and what solution would you suggest to overcome the disadvantages for this case?

*Berikan komen kelebihan dan kekurangan aplikasi MPC yang berkaitan dengan strategi kawalan bioreaktor ini dan apakah penyelesaian yang akan anda cadangkan untuk mengatasi kekurangan MPC dalam kes ini.*

*[4 marks/markah]*

4.

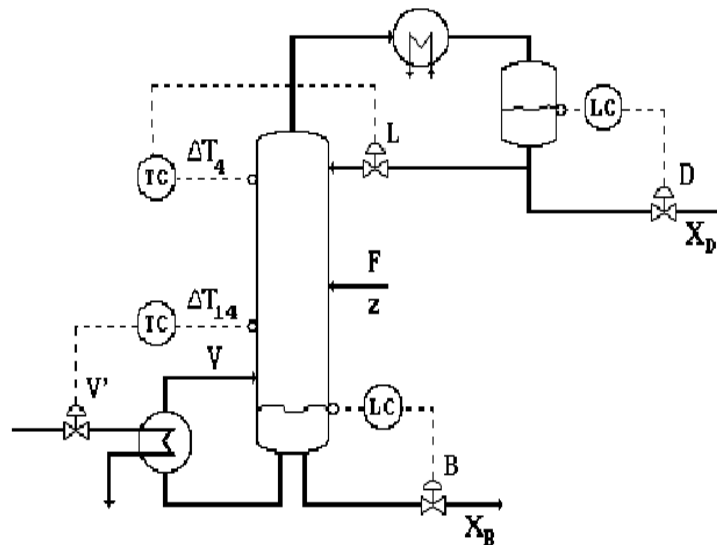


Figure Q.4.: A Binary Distillation Column in LV Configuration.

*Rajah S.4.: LV Konfigurasi untuk turus penyulingan perduaan.*

Figure Q.4. shows the flowsheet for the two-point composition control in a binary distillation column. Of the four control variables available, two are used for inventory control, leaving vapor boil-up rate,  $V$ , and reflux flow,  $L$ , to control top and bottom compositions,  $X_D$  and  $X_B$ . The column disturbances are feed composition,  $X_F$ , and flow rate,  $F$ . The column dynamics have been approximated by a linear model in the transfer function form as shown below:

Rajah S.4. menunjukkan carta alir kawalan dua titik komposisi untuk turus penyulingan perduaan. Daripada empat pembolehubah yang sedia ada, dua telah digunakan untuk kawalan hasil keluaran, meninggalkan kadar wap didih,  $V$ , dan aliran refluk,  $L$ , mengawal komposisi di atas dan bawah,  $X_D$  dan  $X_B$ . Gangguan untuk turus ini ialah komposisi suapan,  $X_F$  dan aliran suapan,  $F$ . Dinamik turus telah di anggapkan sebagai model lurus seperti fungsi pemindahan yang ditunjukkan di bawah:

$$\begin{bmatrix} x_D \\ x_B \end{bmatrix} = \begin{bmatrix} \frac{-0.045}{8.1s+1} e^{-0.5s} & \frac{0.048}{11s+1} e^{-0.5s} \\ \frac{-0.23}{8.1s+1} e^{-1.5s} & \frac{0.55}{10s+1} e^{-0.5s} \end{bmatrix} \begin{bmatrix} L \\ V \end{bmatrix} \\ + \begin{bmatrix} \frac{-0.001}{10s+1} e^{-s} & \frac{0.004}{8.5s+1} e^{-s} \\ \frac{-0.16}{5.5s+1} e^{-s} & \frac{-0.65}{9.2s+1} e^{-s} \end{bmatrix} \begin{bmatrix} F \\ x_F \end{bmatrix}$$

- [a] Calculate the relative gain of the loop and hence calculate the relative gain array for the servo control.

*Kirakan gandaan relatif bagi gelung dan kirakan juga tatasusunan gandaan relatif bagi kawalan servo.*

[2 marks/markah]

- [b] Using the relative gain array, make comments on the selection of control loop pairing for two single loop controllers.

*Dengan menggunakan tatasusunan gandaan relatif, berikan komen pada pemilihan pasangan gelung kawalan bagi dua pengawal gelung tunggal.*

[2 marks/markah]

- [c] To assess system sensitivity, the engineer considers:

*Untuk menilai kepekaan sistem, jurutera harus mempertimbangkan:*

[i] a change in  $mv1(s)$  of magnitude 1 with  $mv2(s)$  held constant  
*perubahan magnitud 1 pada  $mv1(s)$  dengan  $mv2(s)$  ditetapkan malar*

[ii] a change in  $mv2(s)$  of magnitude 1 with  $mv1(s)$  held constant  
*perubahan magnitud 1 pada  $mv2(s)$  dengan  $mv1(s)$  ditetapkan malar*

What are the effective gains that correspond to this input direction?

*Apakah gandaan berkesan yang sepadan bagi arah suapan tersebut?*

[4 marks/markah]

- [d] If the ratio of the two effective gains is the condition number of the plant, what is significance of the two effective gains? Please confirm your answer.

*Jika nisbah bagi dua gandaan berkesan adalah syarat bagi nombor keadaan sesebuah loji, apakah kepentingan dua gandaan berkesan tersebut? Sila pastikan jawapan anda.*

*[2 marks/markah]*

- [e] Using the value obtained for the condition number in [d] make comments about the sensitivity of the plant and the feasibility for applying a decoupling control law. Then, design an ideal decoupling control scheme for this system.

*Dengan menggunakan nilai yang diperolehi untuk nombor keadaan pada [d] berikan komen mengenai kepekaan loji dan kesesuaian penggunaan hukum kawalan tak berpasangan. Selepas itu, rekabentukkan satu skema kawalan unggul kawalan tak berpasangan bagi sistem ini.*

*[12 marks/markah]*

- [f] Draw a block diagram representation of the decoupling control scheme indicating the positions of all the transfer function and the additional feedback controllers.

*Lukiskan gambarajah blok yang mewakili struktur sistem kawalan tak berpasangan dengan menunjukkan kedudukan semua rangkap pindah dan tambahan pengawal suap balik.*

*[3 marks/markah]*



Appendix

Table Laplace Transforms for Various Time-Domain Functions<sup>a</sup>

| $f(t)$  | $F(s)$   |
|---|--|
| 1. $\delta(t)$ (unit impulse)   | 1  |
| 2. $S(t)$ (unit step)   | $\frac{1}{s}$  |
| 3. $t$ (ramp)   | $\frac{1}{s^2}$  |
| 4. $t^{n-1}$  | $\frac{(n-1)!}{s^n}$   |
| 5. $e^{-bt}$  | $\frac{1}{s+b}$  |
| 6. $\frac{1}{\tau} e^{-t/\tau}$   | $\frac{1}{\tau s + 1}$   |
| 7. $\frac{t^{n-1} e^{-bt}}{(n-1)!}$ ( $n > 0$ )   | $\frac{1}{(s+b)^n}$  |
| 8. $\frac{1}{\tau^n (n-1)!} t^{n-1} e^{-t/\tau}$  | $\frac{1}{(\tau s + 1)^n}$   |
| 9. $\frac{1}{b_1 - b_2} (e^{-b_2 t} - e^{-b_1 t})$  | $\frac{1}{(s+b_1)(s+b_2)}$   |
| 10. $\frac{1}{\tau_1 - \tau_2} (e^{-t/\tau_1} - e^{-t/\tau_2})$   | $\frac{1}{(\tau_1 s + 1)(\tau_2 s + 1)}$   |
| 11. $\frac{b_3 - b_1}{b_2 - b_1} e^{-b_1 t} + \frac{b_3 - b_2}{b_1 - b_2} e^{-b_2 t}$   | $\frac{s + b_3}{(s+b_1)(s+b_2)}$   |
| 12. $\frac{1}{\tau_1} \frac{\tau_1 - \tau_3}{\tau_1 - \tau_2} e^{-t/\tau_1} + \frac{1}{\tau_2} \frac{\tau_2 - \tau_3}{\tau_2 - \tau_1} e^{-t/\tau_2}$                       | $\frac{\tau_3 s + 1}{(\tau_1 s + 1)(\tau_2 s + 1)}$  |
| 13. $1 - e^{-t/\tau}$   | $\frac{1}{s(\tau s + 1)}$  |
| 14. $\sin \omega t$   | $\frac{\omega}{s^2 + \omega^2}$  |
| 15. $\cos \omega t$   | $\frac{s}{s^2 + \omega^2}$   |
| 16. $\sin(\omega t + \phi)$   | $\frac{\omega \cos \phi + s \sin \phi}{s^2 + \omega^2}$  |
| 17. $e^{-bt} \sin \omega t$   | $\left\{ \begin{array}{l} \frac{\omega}{(s+b)^2 + \omega^2} \\ \frac{s+b}{(s+b)^2 + \omega^2} \end{array} \right.$ |
| 18. $e^{-bt} \cos \omega t$   |  |
| 19. $\frac{1}{\tau \sqrt{1-\zeta^2}} e^{-\zeta t/\tau} \sin(\sqrt{1-\zeta^2} t/\tau)$<br>( $0 \leq  \zeta  < 1$ )   | $\frac{1}{\tau^2 s^2 + 2\zeta \tau s + 1}$   |
| 20. $1 + \frac{1}{\tau_2 - \tau_1} (\tau_1 e^{-t/\tau_1} - \tau_2 e^{-t/\tau_2})$<br>( $\tau_1 \neq \tau_2$ )   | $\frac{1}{s(\tau_1 s + 1)(\tau_2 s + 1)}$  |
| 21. $1 - \frac{1}{\sqrt{1-\zeta^2}} e^{-\zeta t/\tau} \sin[\sqrt{1-\zeta^2} t/\tau + \psi]$<br>$\psi = \tan^{-1} \frac{\sqrt{1-\zeta^2}}{\zeta}$ , ( $0 \leq  \zeta  < 1$ ) | $\frac{1}{s(\tau^2 s^2 + 2\zeta \tau s + 1)}$  |
| 22. $1 - e^{-\zeta t/\tau} [\cos(\sqrt{1-\zeta^2} t/\tau) + \frac{\zeta}{\sqrt{1-\zeta^2}} \sin(\sqrt{1-\zeta^2} t/\tau)]$<br>( $0 \leq  \zeta  < 1$ )                      | $\frac{1}{s(\tau^2 s^2 + 2\zeta \tau s + 1)}$  |
| 23. $1 + \frac{\tau_3 - \tau_1}{\tau_1 - \tau_2} e^{-t/\tau_1} + \frac{\tau_3 - \tau_2}{\tau_2 - \tau_1} e^{-t/\tau_2}$<br>( $\tau_1 \neq \tau_2$ )                         | $\frac{\tau_3 s + 1}{s(\tau_1 s + 1)(\tau_2 s + 1)}$   |
| 24. $\frac{df}{dt}$   | $sF(s) - f(0)$   |
| 25. $\frac{d^n f}{dt^n}$  | $s^n F(s) - s^{n-1} f(0) - s^{n-2} f^{(1)}(0) - \dots - s f^{(n-2)}(0) - f^{(n-1)}(0)$                             |
| 26. $f(t - t_0)S(t - t_0)$  | $e^{-t_0 s} F(s)$  |

<sup>a</sup>Note that  $f(t)$  and  $F(s)$  are defined for  $t \geq 0$  only.