UNIVERSITI SAINS MALAYSIA

Second Semester Examination
Academic Session 2004/2005

*Peperiksaan Semester Kedua*
*Sidang Akademik 2004/2005*

March 2005
*Mac 2005*

# EKC 361E – Dynamic & Process Control
# *[Dinamik & Kawalan Proses]*

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

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

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

**Instruction:** Answer **FOUR (4)** questions. Answer any **TWO (2)** questions from Section A. Answer any **TWO (2)** questions from Section B.

*[**Arahan:** Jawab **EMPAT (4)** soalan. Jawab mana-mana **DUA (2)** soalan dari Bahagian A. Jawab mana-mana **DUA (2)** soalan dari Bahagian B.]*

*[Pelajar dibenarkan menjawab semua soalan dalam Bahasa Inggeris ATAU Bahasa Malaysia ATAU kombinasi kedua-duanya.]*

Section A : Answer any TWO questions.
*Bahagian A : Jawab mana-mana DUA soalan.*

1. [a] For each of the following cases, determine what functions of time, e.g., constant, $e^{-8t}$, will appear in y(t). (Note that you do not have to find $y(t)$!) Which $y(t)$ are oscillatory? Which exhibit a constant value of $y(t)$ for large values of $t$?

[i] $Y(s)=\dfrac{2}{s(s^2+4s)}$

[ii] $Y(s)=\dfrac{2}{s(s^2+4s+3)}$

[iii] $Y(s)=\dfrac{2}{s(s^2+4s+4)}$

[iv] $Y(s)=\dfrac{2}{s(s^2+4s+8)}$

*[12 marks]*

[b] Consider the following transfer function:

$$G(s)=\frac{Y(s)}{U(s)}=\frac{5}{10s+1}$$

[i] What is the steady-state gain?

[ii] What is the time constant?

[iii] If $U(s) = 2/s$, what is the value of the output $y(t)$ when $t \longrightarrow \infty$?

[iv] For the same $U(s)$, what is the value of the output when $t = 10$?

[v] If $U(s)=(1-e^{-s})/s$, that is, the unit rectangular pulse, what is the output when $t \longrightarrow \infty$?

[vi] If $u(t)=2\sin 3t$, what is the value of the output $y(t)$ when $t \longrightarrow \infty$?

*[13 marks]*

*1. [a] Bagi setiap kes yang berikut, tentukan fungsi masa sebagai contoh, $e^{-8t}$ yang akan ditemui dalam y(t). (Perhatikan bahawa anda tidak perlu mencari y(t)!) y(t) yang manakah berayun? y(t) yang manakah akan memperlihatkan nilai malar untuk nilai t yang besar?*

*[i]* $Y(s)=\dfrac{2}{s(s^2+4s)}$

*[ii]* $Y(s)=\dfrac{2}{s(s^2+4s+3)}$

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*[iii]* $Y(s) = \dfrac{2}{s(s^2 + 4s + 4)}$

*[iv]* $Y(s) = \dfrac{2}{s(s^2 + 4s + 8)}$

*[12 markah]*

*[b]* *Pertimbangkan rangkap pindah yang berikut:*

$$G(s) = \frac{Y(s)}{U(s)} = \frac{5}{10s + 1}$$

*[i]* *Apakah gandaan keadaan mantapnya?*

*[ii]* *Apakah masa malarnya?*

*[iii]* *Jika U(s) = 2/s, Apakah nilai keluaran y(t) apabila* $t \longrightarrow \infty$*?*

*[iv]* *Bagi U(s) yang sama, apakah nilai keluaran apabila t = 10?*

*[v]* *Jika* $U(s) = (1 - e^{-s})/s$, *iaitu unit denyut segiempat tepat, apakah keluaran apabila* $t \longrightarrow \infty$*?*

*[vi]* *Jika* $u(t) = 2\sin 3t$, *apakah nilai keluaran y(t) apabila* $t \longrightarrow \infty$*?*

*[13 markah]*

2. [a] The overall transfer function of a process is given by

$$G = G_1 G_2$$

where $G_1 = \dfrac{K_1}{\tau_1 s + 1}$ and $G_2 = \dfrac{K_2}{\tau_2 s + 1}$ with $\tau_1 = 5$ and $\tau_2 = 3$.

[i] What is the overall gain of $G$?

[ii] Derive the expression for a unit step response of the process.

*[10 marks]*

[b] Write down the parallel form of PID controller in time domain and Laplace domain and explain briefly.

*[5 marks]*

[c] A block diagram for internal model control is shown in Figure Q.2.[a]. Transfer function $\widetilde{G}_p$ denotes the process model, while $G_p$ denotes the actual process transfer function. It has been assumed that $G_v = G_m = 1$ for simplicity. Derive closed-loop transfer functions for both the servo and regulator problems.

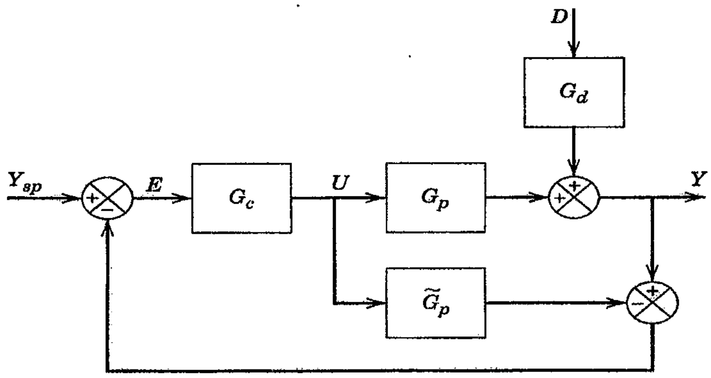



Figure Q.2. [a]

*[10 marks]*

2. *[a] Rangkap pindah keseluruhan sebuah proses diberi sebagai*

$$G = G_1G_2$$

*Di mana* $G_1 = \dfrac{K_1}{\tau_1 s + 1}$ *dan* $G_2 = \dfrac{K_2}{\tau_2 s + 1}$ *dengan* $\tau_1 = 5$ *dan* $\tau_2 = 3$.

*[i] Apakah gandaan keseluruhan G?*

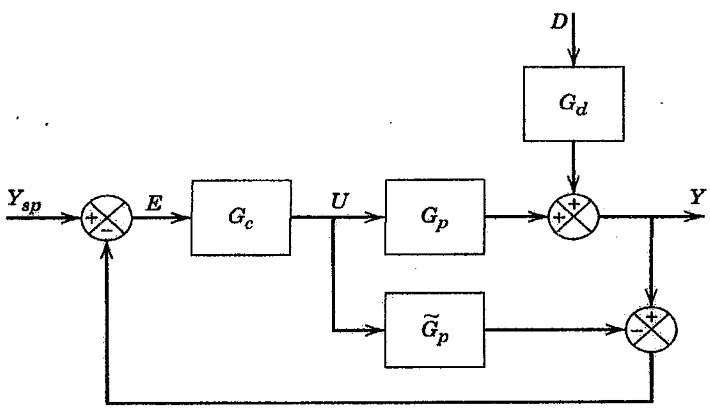
*[ii] Terbitkan ungkapan bagi sambutan satu unit langkah bagi proses tersebut.*

*[10 markah]*

*[b] Tuliskan bentuk selari pengawal PID di dalam domain masa dan domain Laplace dan terangkan secara ringkas.*

*[5 marka*

*[c] Gambarajah blok bagi kawalan model dalaman ditunjukkan dalam Rajah S.2.[a]. Rangkap pindah* $\tilde{G}_p$ *menandakan model proses, manakala* $G_p$ *menandakan rangkap pindah proses yang sebenar. Andaikan* $G_v = G_m = 1$. *Terbitkan rangkap pindah gegelung tertutup bagi kedua-dua masalah servo dan pengatur.*




*Rajah S.2. [a]*

*[10 markah]*

3. [a] Consider the closed-loop block diagram of the feedback system shown in Figure Q.3. [a].

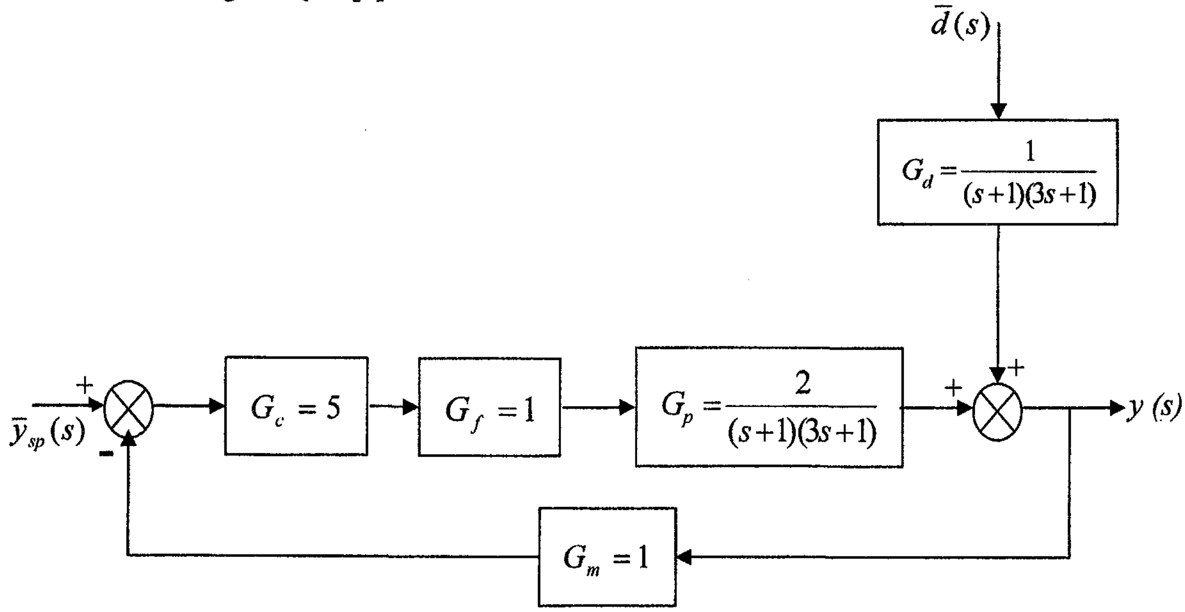



Figure Q. 3. [a]

For a set point step change of magnitude 2, do the following:

[i] Derive an expression for the closed-loop response in the Laplace domain.

[ii] Find how the closed-loop output responds with time to the set point step change above.

[iii] Compute the maximum value of $y(t)$ and state when it occurs.

[iv] Compute the offset of the final steady state.

[v] Compute the period of oscillation of the closed-loop response.

[vi] Give a qualitative sketch of the closed-loop response.

*Hint: You may use the following analytical expressions for some of the characteristics of an underdamped second-order process:*

Overshoot: $\text{OS} = \exp\left(-\pi\zeta / \sqrt{1-\zeta^2}\right)$

Time to first peak: $t_m = \pi\tau / \sqrt{1-\zeta^2}$

Period: $P = \dfrac{2\pi\tau}{\sqrt{1-\zeta^2}}$

*[13 marks]*

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[b] Consider the following unity feedback system in Figure Q.3. [b]

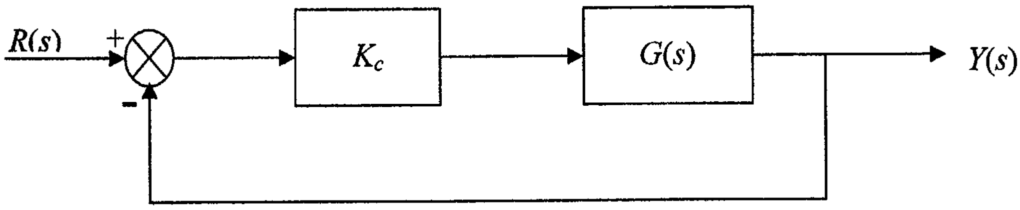


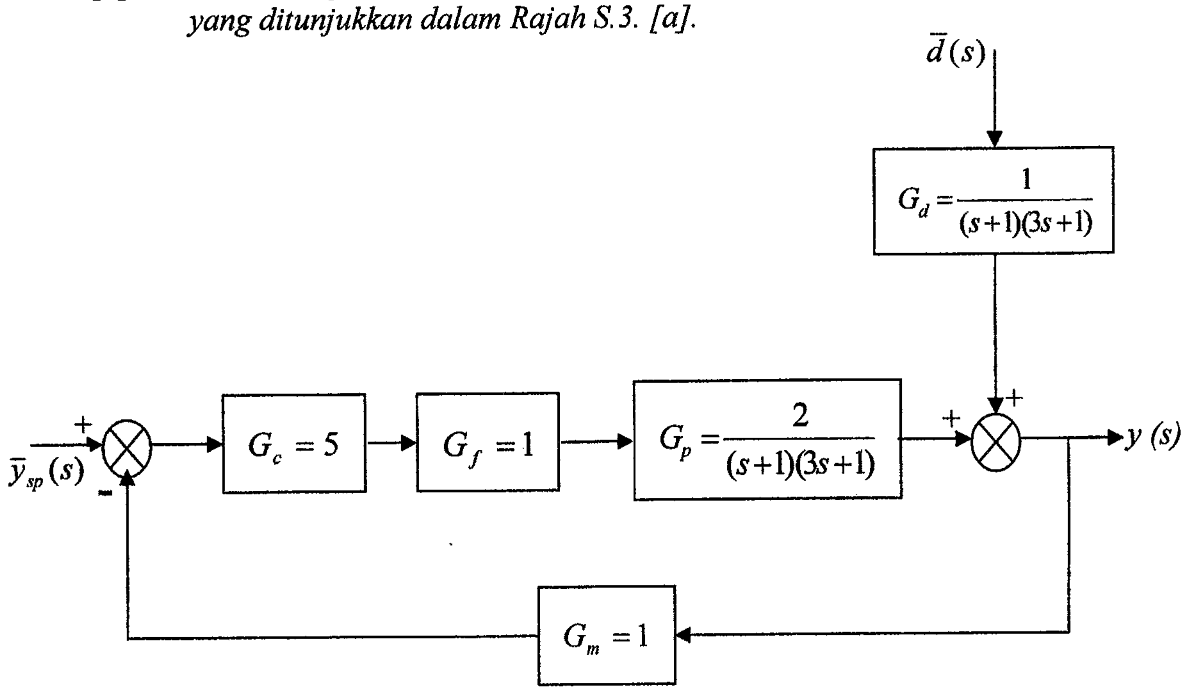

Figure Q.3. [b]

If $G(s) = \dfrac{(s+6)}{s(s+1)(s+3)}$, determine the range of values of $K_c$ for stability.

*Hint: Use Routh array method.*

*[12 marks]*

3. *[a] Pertimbangkan gambarajah blok gegelung tertutup bagi sistem suap balik yang ditunjukkan dalam Rajah S.3. [a].*




*Rajah S.3 [a]*

*Bagi perubahan langkah titik set bermagnitud 2, lakukan yang berikut:*

*[i] Terbitkan ungkapan sambutan gegelung tertutup dalam domain Laplace*

*[ii] Tentukankan bagaimana sambutan keluaran gegelung tertutup dengan masa bagi perubahan langkah titik set di atas.*

*[iii] Kirakan nilai maksimum y(t) dan nyatakan bilakah ianya berlaku.*

...7/-

*[iv]* *Kirakan ofset bagi keadaan mantap akhir.*

*[v]* *Kirakan tempoh ayunan bagi sambutan gegelung tertutup.*

*[vi]* *Berikan lakaran kualitatif sambutan gegelung tertutup.*

*Petunjuk:* *Anda boleh gunakan ungkapan analitis yang berikut bagi sesetengah ciri proses tertib kedua bawah redam*

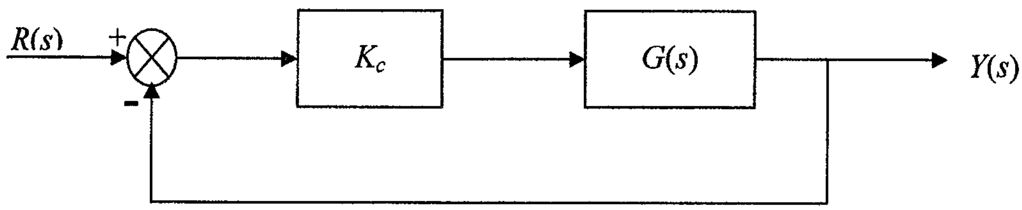
*Tembak lebih:* $OS = \exp\left(-\pi\zeta / \sqrt{1-\zeta^2}\right)$

*Masa untuk puncak pertama:* $t_m = \pi\tau / \sqrt{1-\zeta^2}$

*Tempoh:* $P = \dfrac{2\pi\tau}{\sqrt{1-\zeta^2}}$

*[13 markah]*

*[b]* *Pertimbangkan sistem suap balik dalam Rajah S.3. [b]*




*Rajah S.3. [b]*

*Jika* $G(s) = \dfrac{(s+6)}{s(s+1)(s+3)}$, *tentukan julat nilai* $K_c$ *untuk kestabilan.*
*Petunjuk : Gunakan kaedah tatasusunan Routh.*

*[12 markah]*

Section B : Answer any TWO questions.
*Bahagian B : jawab mana-mana DUA Soalan.*

4. [a] Briefly explain the following :-

[i] Systematic error, random error and total error

[ii] Dynamic measurement error

[iii] Transmitter and transducer

[iv] Thermocouple

*[16 marks]*
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[b] Several linear transmitters have been installed and calibrated as follows:

| | | | |
|---|---|---|---|
| Flow rate : | 400 gal/min → 15 psig | | pneumatic |
| | 0 gal/min → 3 psig | | transmitter |
| Pressure : | 30 in Hg → 20 mA | | current |
| | 10 in Hg → 4 mA | | transmitter |
| Level : | 20 m → 5VDC | | voltage |
| | 0.5 m → 1 VDC | | transmitter |
| Concentration : | 20g/L → 10VDC | | voltage |
| | 2g/L → 1 VDC | | transmitter |

[i] Develop an expression for the output of each transmitter as a function of its input. Be sure to include appropriate units.

[ii] What is the gain, span and zero of each transmitter? Is the gain constant or variable?

*[9 marks]*

4. *[a] Terangkan secara ringkas perkara-perkara berikut :-*

*[i] Ralat sistematik, ralat rawak dan jumlah ralat*

*[ii] Ralat pengukuran dinamik*

*[iii] Pengantar dan transduser*

*[iv] Pengganding suhu*

*[16 markah]*

*[b] Beberapa pengantar lelurus telah dipasang dan telah ditentukurkan seperti berikut:*

| | | | |
|---|---|---|---|
| *Kadar aliran :* | *400 gal/min → 15 psig* | | *pengantar* |
| | *0 gal/min → 3 psig* | | *peneumatik* |
| *Tekanan :* | *30 in Hg → 20 mA* | | *pengantar* |
| | *10 in Hg → 4 mA* | | *arus* |
| *Aras :* | *20 m → 5VDC* | | *pengantar* |
| | *0.5 m → 1 VDC* | | *voltan* |
| *Kepekatan :* | *20g/L → 10VDC* | | *pengantar* |
| | *2g/L → 1 VDC* | | *voltan* |

*[i] Bangunkan ungkapan bagi setiap pengantar sebagai fungsi masukan masing-masing. Pastikan unit-unit yang sepatutnya dimasukkan.*

*[ii] Apakah gandaan, rentang dan sifar bagi setiap pengantar? Adakah gandaan tersebut pemalar atau pembolehubah?*

*[9 markah]*

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5. [a] Consider the stirred tank heating system shown in Figure Q.5. [a]

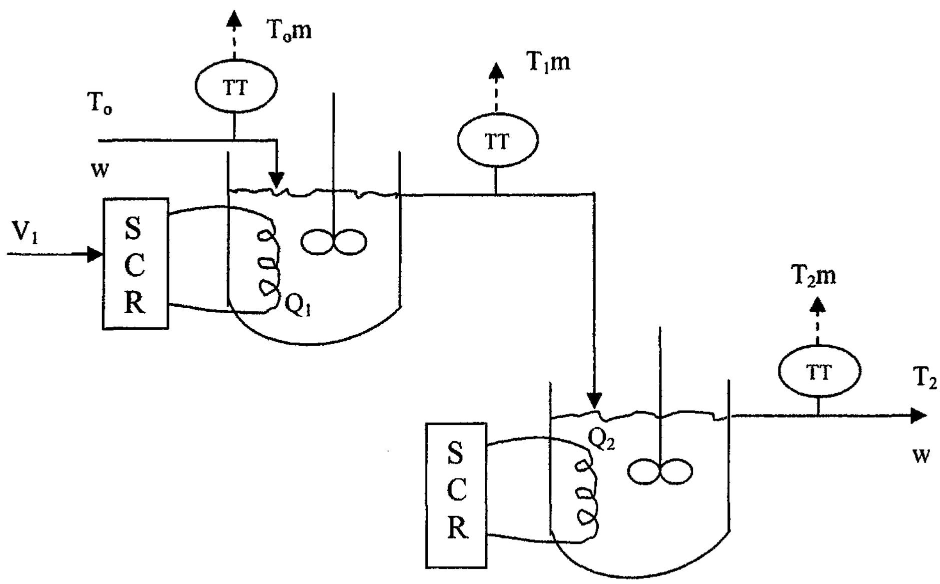


Figure Q.5. [a] Stirred Tank

It is desired to control temperature $T_2$ by adjusting the heating rate $Q_1$ (J/h) via voltage signal $V_1$ to the SCR. It has been suggested that measurements of $T_1$ and $T_o$, as well as $T_2$ could provide improved control of $T_2$.

[i] Briefly describe how such a control system might operate and sketch a schematic diagram. State any assumptions that you make.

*[6 marks]*

[ii] Indicate how you would classify your control scheme for example, feedback, cascade or feedforward. Briefly justify your answer.

*[3 marks]*

[iii] Draw a block diagram for the control system.

*[7 marks]*

[b] [i] In your own word discuss the feedforward control design criteria. Give process examples in which feedforward control is appropriate and not appropriate.

[ii] In feedforward-feedback control strategy, which controller should be tuned first? What would be the effect of reversing the order of tuning? Clearly state any assumptions you have used.

*[9 marks]*

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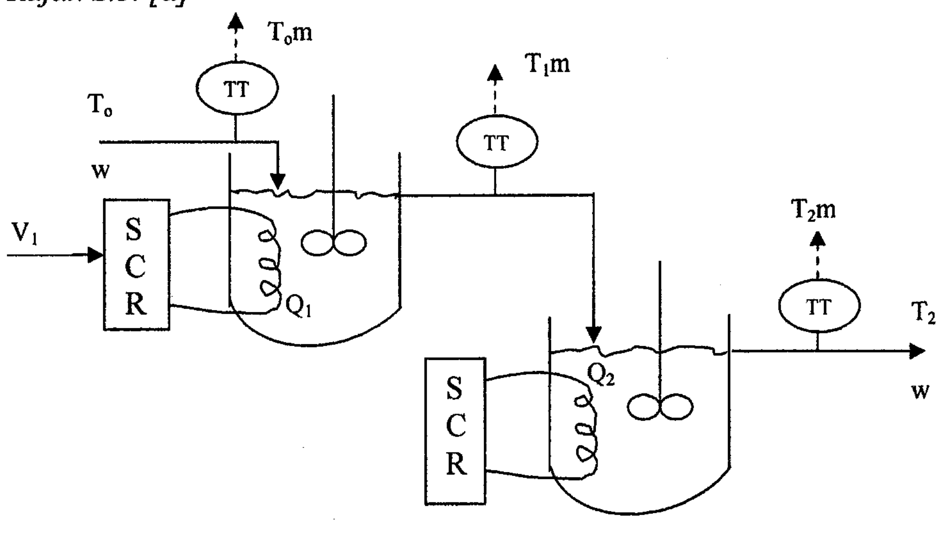
5. [a] *Pertimbangkan sistem pemanas tangki teraduk yang ditunjukkan dalam Rajah S.5. [a]*




*Rajah S.5. [a] Tangki Teraduk*

*Suhu $T_2$ boleh dikawal dengan melaras kadar pemanasan $Q_1$ (J/jam) melalui isyarat voltan $V_1$ kepada SCR. Adalah dicadangkan bahawa pengukuran $T_1$ dan $T_o$, serta $T_2$ boleh meningkatkan kawalan terhadap $T_2$.*

[i] *Terangkan secara ringkas bagaimana satu sistem kawalan boleh beroperasi dan lakarkan gambarajah skemanya. Nyatakan sebarang anggapan yang anda buat.*

*[6 markah]*

[ii] *Tunjukkan bagaimana anda boleh mengkelaskan skema kawalan anda sebagai contoh suap-balik, lata atau suap-depan. Jelaskan secara ringkas jawapan anda.*

*[3 markah]*

[iii] *Lukiskan gambarajah blok bagi sistem kawalan tersebut.*

*[7 markah]*

[b] [i] *Dengan menggunakan perkataan anda sendiri, bincangkan ciri-ciri rekabentuk kawalan suap-depan. Berikan satu contoh proses di mana kawalan suap-depan adalah sesuai dan satu contoh di mana kawalan suap-depan tidak sesuai.*

[ii] *Dalam strategi kawalan suap-depan-suap-balik, pengawal mana mesti ditala dahulu? Apakah kesan sekiranya turutan talaan diterbalikkan. Nyatakan dengan jelas bagi sebarang anggapan yang digunakan.*

*[9 markah]*

6. [a] Data has been collected from a chemical reactor. The inlet concentration was the only input variable that changed when the data was collected. The input and output data is given in Table Q.6. [a]

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[i] Plot these data to obtain a process reaction curve.

*[6 marks]*

[ii] Perform the process reaction curve calculations and report the model parameters.

*[10 marks]*

[iii] Determine the PID controller parameters using your answer in part [ii].

*[3 marks]*

Given: PID:

$$K_C = \frac{1}{K}\frac{\tau}{\theta}\left[\frac{16\tau + 3\theta}{12\tau}\right]$$

$$\tau_I = \frac{\theta\left[32 + 6(\theta/\tau)\right]}{13 + 8(\theta/\tau)}$$

$$\tau_D = \frac{4\theta}{11 + 2(\theta/\tau)}$$

Table Q.6. [a] : Data collected from a chemical reactor

| Time (min) | Input (%open) | Output (°C) |
|---|---|---|
| 0 | 30 | 69.65 |
| 4 | 30 | 69.70 |
| 8 | 30 | 70.41 |
| 12 | 30 | 70.28 |
| 16 | 30 | 69.55 |
| 20 | 30 | 70.32 |
| 24 | 38 | 69.97 |
| 28 | 38 | 69.96 |
| 32 | 38 | 69.68 |
| 36 | 38 | 70.22 |
| 40 | 38 | 71.32 |
| 44 | 38 | 72.33 |
| 48 | 38 | 72.92 |
| 52 | 38 | 73.45 |
| 56 | 38 | 74.09 |
| 60 | 38 | 75.00 |
| 64 | 38 | 75.25 |
| 68 | 38 | 74.78 |
| 72 | 38 | 75.27 |
| 76 | 38 | 75.97 |
| 80 | 38 | 76.30 |
| 84 | 38 | 76.30 |
| 88 | 38 | 75.51 |
| 92 | 38 | 74.86 |
| 96 | 38 | 75.86 |
| 100 | 38 | 76.20 |
| 104 | 38 | 76.0 |

[b] A PID controller is used to control the temperature of a jacketed batch reactor by adjusting the flow rate of coolant to the jacket. The temperature controller has been tuned to provide satisfactory control at the nominal operating conditions. Would you expect that the temperature controller may have to be retuned for any of the following instrumentation changes.

[i] The span of the temperature transmitter is reduced from 30 to 15°C

[ii] The zero of the temperature transmitter is increased from 50 to 60°C

[iii] The temperature of the coolant leaving the jacket is used as the controlled variable instead of the temperature in the reactor.

*[6 marks]*

6. *[a] Data telah diperolehi daripada sebuah reaktor kimia. Hanya kepekatan masukan merupakan pembolehubah masukan yang berubah apabila data dipungut. Data masukan dan keluaran diberi dalam Jadual S.6. [a]*

*[i] Plot data tersebut untuk mendapatkan lengkung tindak balas proses.*

*[6 markah]*

*[ii] Lakukan pengiraan lengkuk tindak balas proses tersebut dan nyatakan parameter model tersebut.*

*[10 markah]*

*[iii] Tentukan parameter pengawal PID dengan menggunakan jawapan anda dalam bahagian [ii].*

*[3 markah]*

*Diberi:*

*PID:*

$$K_C = \frac{1}{K}\frac{\tau}{\theta}\left[\frac{16\tau + 3\theta}{12\tau}\right]$$

$$\tau_I = \frac{\theta\left[32 + 6\left(\theta/\tau\right)\right]}{13 + 8\left(\theta/\tau\right)}$$

$$\tau_D = \frac{4\theta}{11 + 2\left(\theta/\tau\right)}$$

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*Jadual S.6. [a] : Data diperoleh daripada sebuah reaktor kimia*

| Masa (min) | Masukan (% buka) | Keluaran (°C) |
|---|---|---|
| 0 | 30 | 69.65 |
| 4 | 30 | 69.70 |
| 8 | 30 | 70.41 |
| 12 | 30 | 70.28 |
| 16 | 30 | 69.55 |
| 20 | 30 | 70.32 |
| 24 | 38 | 69.97 |
| 28 | 38 | 69.96 |
| 32 | 38 | 69.68 |
| 36 | 38 | 70.22 |
| 40 | 38 | 71.32 |
| 44 | 38 | 72.33 |
| 48 | 38 | 72.92 |
| 52 | 38 | 73.45 |
| 56 | 38 | 74.09 |
| 60 | 38 | 75.00 |
| 64 | 38 | 75.25 |
| 68 | 38 | 74.78 |
| 72 | 38 | 75.27 |
| 76 | 38 | 75.97 |
| 80 | 38 | 76.30 |
| 84 | 38 | 76.30 |
| 88 | 38 | 75.51 |
| 92 | 38 | 74.86 |
| 96 | 38 | 75.86 |
| 100 | 38 | 76.20 |
| 104 | 38 | 76.0 |

[b] *Pengawal PID digunakan untuk mengawal suhu bagi reaktor teraduk berjaket dengan melaras kadar aliran penyejuk ke jaket. Pengawal suhu tersebut telah ditala untuk menghasilkan kawalan yang memuaskan pada keadaan operasi normal. Adakah anda jangkakan bahawa pengawal suhu perlu ditala semula jika berlakunya perubahan-perubahan pada alatan seperti berikut:*

[i] *Rentang bagi pengantar suhu berkurang daripada 30 kepada 15°C.*

[ii] *Sifar bagi pengantar suhu meningkat daripada 50 kepada 60°C.*

[iii] *Suhu bagi penyejuk yang meninggalkan jaket digunakan sebagai pembolehubah kawalan menggantikan suhu reaktor.*

*[6 markah]*

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## Lampiran

Table Laplace Transforms for Various Time-Domain Functions[a]

| $f(t)$ | $F(s)$ |
|---|---|
| 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. $\frac{1}{b_1-b_2}(e^{-b_2t}-e^{-b_1t})$ | $\frac{1}{(s+b_1)(s+b_2)}$ |
| 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. $\frac{b_3-b_1}{b_2-b_1}e^{-b_1t}+\frac{b_3-b_2}{b_1-b_2}e^{-b_2t}$ | $\frac{s+b_3}{(s+b_1)(s+b_2)}$ |
| 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. $e^{-bt}\sin\omega t$ ($b, \omega$ real) | $\frac{\omega}{(s+b)^2+\omega^2}$ |
| 18. $e^{-bt}\cos\omega t$ ($b, \omega$ real) | $\frac{s+b}{(s+b)^2+\omega^2}$ |
| 19. $\frac{1}{\tau\sqrt{1-\zeta^2}}e^{-\zeta t/\tau}\sin(\sqrt{1-\zeta^2}\,t/\tau)$ $(0\le\lvert\zeta\rvert<1)$ | $\frac{1}{\tau^2s^2+2\zeta\tau s+1}$ |
| 20. $1+\frac{1}{\tau_2-\tau_1}(\tau_1e^{-t/\tau_1}-\tau_2e^{-t/\tau_2})$ $(\tau_1\ne\tau_2)$ | $\frac{1}{s(\tau_1 s+1)(\tau_2 s+1)}$ |
| 21. $1-\frac{1}{\sqrt{1-\zeta^2}}e^{-\zeta t/\tau}\sin[\sqrt{1-\zeta^2}\,t/\tau+\psi]$, $\psi=\tan^{-1}\frac{\sqrt{1-\zeta^2}}{\zeta}$, $(0\le\lvert\zeta\rvert<1)$ | $\frac{1}{s(\tau^2s^2+2\zeta\tau s+1)}$ |
| 22. $1-e^{-\zeta t/\tau}[\cos(\sqrt{1-\zeta^2}\,t/\tau)+\frac{\zeta}{\sqrt{1-\zeta^2}}\sin(\sqrt{1-\zeta^2}\,t/\tau)]$ $(0\le\lvert\zeta\rvert<1)$ | $\frac{1}{s(\tau^2s^2+2\zeta\tau s+1)}$ |
| 23. $1+\frac{\tau_3-\tau_1}{\tau_1-\tau_2}e^{-t/\tau_1}+\frac{\tau_3-\tau_2}{\tau_2-\tau_1}e^{-t/\tau_2}$ $(\tau_1\ne\tau_2)$ | $\frac{\tau_3 s+1}{s(\tau_1 s+1)(\tau_2 s+1)}$ |
| 24. $\frac{df}{dt}$ | $sF(s)-f(0)$ |
| 25. $\frac{d^nf}{dt^n}$ | $s^nF(s)-s^{n-1}f(0)-s^{n-2}f^{(1)}(0)-\cdots-sf^{(n-2)}(0)-f^{(n-1)}(0)$ |
| 26. $f(t-t_0)S(t-t_0)$ | $e^{-t_0s}F(s)$ |

[a]Note that $f(t)$ and $F(s)$ are defined for $t\ge 0$ only.