IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2008

EEE/ISE PART II MEng. BEng and ACGI

SIGNALS AND LINEAR SYSTEMS

Time allowed: 2:00 hours

There are FOUR questions on this paper.

Q1 is compulsory.
Answer Q1 and any two of questions 2-4.
Q1 carries 40% of the marks. Questions 2 to 4 carry equal marks (30% each).

Any special instructions for invigilators and information for candidates are on page 1.

First Marker: *Peter Y. K. Cheung*

Second Marker: *M. M. Draief*

Special instructions for invigilators: None

Information for candidates: None

[Question 1 is compulsory]

1. a) With a single equation, define the characteristic of a linear system.

[2]

b) Find the even and odd components of the signal $x(t) = e^{j\theta}$.

[2]

c) A continuous-time signal $x(t)$ is shown in Figure 1.1. Sketch the signals

i) $x(t)[u(t) - u(t-1)]$

[3]

ii) $x(t)\,\delta(t - \frac{3}{2})$.

[3]

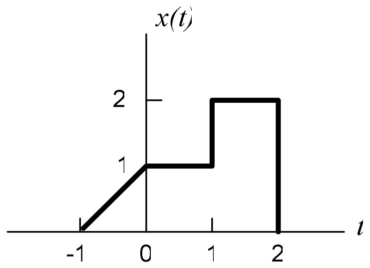


Figure 1.1

d) Consider the RC circuit shown in Figure 1.2. Find the relationship between the input $x(t) = v_s(t)$ and the output $y(t) = i(t)$ in the form of:

i) a differential equation;

[3]

ii) a transfer function.

[3]

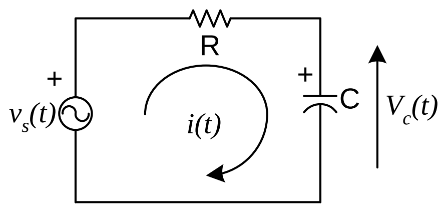


Figure 1.2

e) The unit impulse response of an LTI system is $h(t) = \left[2e^{-3t} - e^{-2t}\right]u(t)$. Find the system's zero-state response $y(t)$ if the input $x(t) = e^{-t}u(t)$. Note that

$$e^{\lambda_1 t}u(t) * e^{\lambda_2 t}u(t) = \frac{e^{\lambda_1 t} - e^{\lambda_2 t}}{\lambda_1 - \lambda_2}u(t) \qquad \text{for } \lambda_1 \neq \lambda_2.$$

[4]

f) Using the graphical method, find $y(t) = x(t) * h(t)$ where $x(t)$ and $h(t)$ are shown in Figure 1.3.

[4]

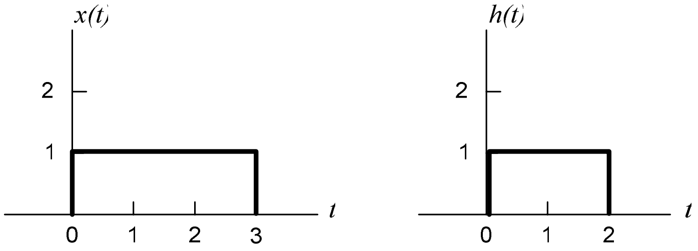


Figure 1.3

g) Find the pole and zero locations for a n system with the transfer function

$$H(s) = \frac{s^2 - s + 5/2}{s^2 + 5s + 4}.$$

[4]

h) Given that the Fourier transform of the signal $x(t)$ is $X(\omega)$, i.e. $x(t) \Leftrightarrow X(\omega)$, prove from first principle that

$$x(t - t_0) \Leftrightarrow e^{-j\omega t_0} X(\omega).$$

[4]

i) Using the z-transform pairs $u[k] \Leftrightarrow \frac{z}{z-1}$ and $\gamma^k u[k] \Leftrightarrow \frac{z}{z-\gamma}$, or otherwise, find the inverse z-transform of

$$F[z] = \frac{z(z-7)}{z^2 - 5z + 4}.$$

[4]

j) A TV signal has a bandwidth of 4.5 MHz. This signal is sampled and quantized with an analogue-to-digital converter.

i) Determine the sampling rate if the signal is to be sampled at a rate 20% above the Nyquist rate.

[2]

ii) If the samples are quantized into 1024 levels, determine the bit-rate (i.e. bits/second) of the binary coded signal.

[2]

2. a) Given the initial conditions $y_0(0)=0$ and $\dot{y}_0(0)=1$, find the unit impulse response of an LTI system specified by the equation

$$\frac{d^2y}{dt^2}+6\frac{dy}{dt}+9y(t)=2\frac{dx}{dt}+9x(t).$$

[15]

b) An input signal $f(t)$ is expressed in terms of step components as shown in Figure 2.1. The step component at time $t=\tau$ has a height of Δf which can be expressed as

$$\Delta f=\frac{\Delta f}{\Delta\tau}\Delta\tau=\dot{f}(\tau)\Delta\tau.$$

If $g(t)$ is the unit step response of an LTI system to the step input $u(t)$, show that the zero-state response $y(t)$ of the system to the input $f(t)$ can be expressed as

$$y(t)=\int_{-\infty}^{\infty}\dot{f}(\tau)g(t-\tau)d\tau=\dot{f}(t)*g(t).$$

[15]

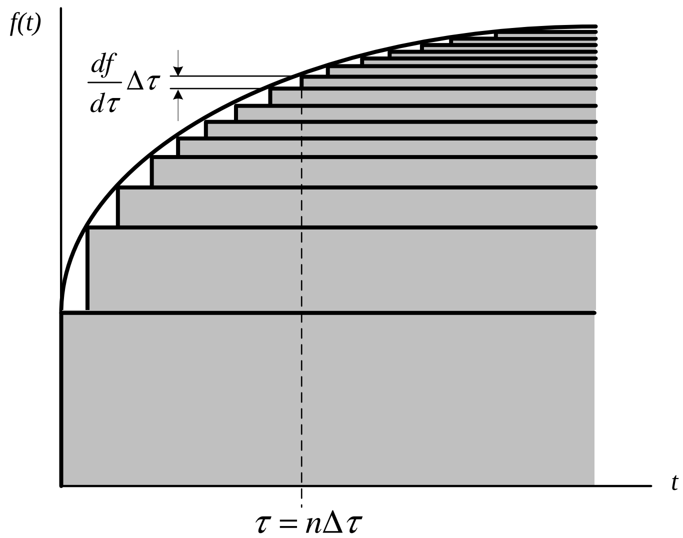


Figure 2.1

3. a) Find the Fourier transform of the signal shown in Figure 3.1 using two different methods:

   i) By direct integration using the definition of the Fourier transform

[10]

   ii) Using only the time-shifting property and the Fourier transform pair

$$rect\left(\frac{t}{\tau}\right) \Leftrightarrow \tau\, sinc\left(\frac{\omega\tau}{2}\right).$$

[10]

b) Given that $\int_{-\infty}^{\infty} e^{-x^2/2} dx = \sqrt{2\pi}$, show that the energy E_f of a Gaussian pulse

$$f(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{t^2}{2\sigma^2}}$$

is given by

$$E_f = \frac{1}{2\sigma\sqrt{\pi}}.$$

You should derive the energy E_f from $F(\omega)$ using the Parseval's theorem and the following Fourier transform pair

$$e^{-t^2/2\sigma^2} \Leftrightarrow \sigma\sqrt{2\pi}\, e^{-\sigma^2\omega^2/2}.$$

[10]

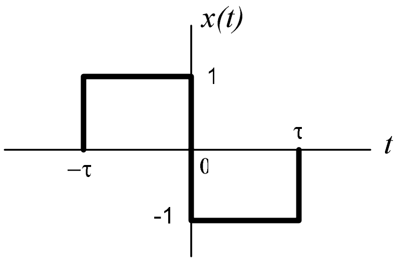


Figure 3.1

4. A discrete-time LTI system is specified by the difference equation

$$y[k+1]-0.5y[k]=f[k+1]+0.8f[k].$$

a) Derive its transfer function in the z-domain.

[6]

b) Find the amplitude and phase response of the system.

[14]

c) Find the system response $y[k]$ for the input $f[k]=\cos(0.5k-\frac{\pi}{3})$.

[10]

[THE END]

E2.5 Signals and Linear Systems
Solutions 2008

All questions are unseen.

Question 1 is compulsory.

Answer to Question 1

a)

If $x_1 \to y_1$ and $x_2 \to y_2$, for a linear system,

$k_1x_1 + k_2x_2 \to k_1y_1 + k_2y_2$ where k_1 and k_2 are constants.

[2]

b)

$$x(t) = e^{j\theta} = \cos\theta + j\sin\theta$$

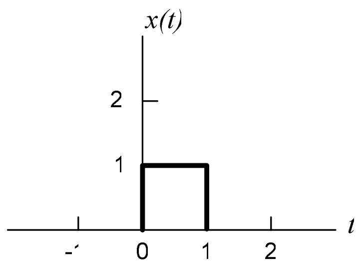
Therefore,

Even: $\cos\theta$

Odd: $j\sin\theta$.

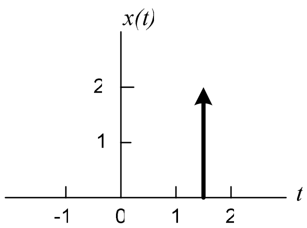
[2]

c) *i*)



[3]

ii)



[3]

d) *i*)

$$v_s(t) = Ri(t) + v_c(t)$$

$$v_c(t) = \frac{1}{C}\int_{-\infty}^{t} i(\tau)d\tau$$

$$x(t) = v_s(t), \quad y(t) = i(t).$$

$$\therefore \quad Ry(t) + \frac{1}{C}\int_{-\infty}^{t} y(\tau)d\tau = x(t).$$

Differentiate both sides wrt *t*:

$$R\frac{dy}{dt} + \frac{1}{C}y(t) = \frac{dx}{dt}$$

$$\Rightarrow \frac{dy}{dt} + \frac{1}{RC}y(t) = \frac{1}{R}\frac{dx}{dt}$$

[3]

ii) Take Laplace transform on both sides:

$$(s + \frac{1}{RC})\, Y(s) = \frac{1}{R} sX(s).$$

$$\therefore H(s) = \frac{Y(s)}{X(s)} = C \times \frac{s}{RCs + 1}.$$

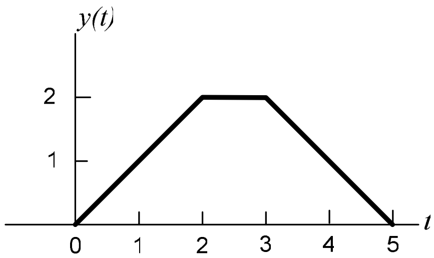
[3]

e)

$$\begin{aligned} y(t) &= h(t) * x(t) \\ &= (2e^{-3t} - e^{-2t})u(t) * e^{-t}u(t) \\ &= 2e^{-3t}u(t) * e^{-t}u(t) - e^{-2t}u(t) * e^{-t}u(t) \\ &= \left[\frac{2(e^{-t} - e^{-3t})}{2} - \frac{(e^{-t} - e^{-2t})}{1}\right]u(t) \\ &= \left(e^{-2t} - e^{-3t}\right)u(t) \end{aligned}$$

[4]

f)



[4]

g) The complex zeros are given by:

$$z^2 - z + \frac{5}{2} = 0.$$

Therefore the zeros are at:

$$z=\frac{1 \pm \sqrt{1\text{-}10}}{2} = \frac{1}{2} \pm j\frac{3}{2}.$$

The poles are given by:

$$p^2 + 5p + 5 = (p+4)(p+1) = 0.$$

Therefore the poles are at:

$$p = -1 \text{ and } p = -4.$$

[4]

h) By definition of Fourier transform,

$$\text{FT of } \; x(t-t_0) = \int_{-\infty}^{\infty} x(t-t_0) e^{-j\omega t} dt .$$

Let $\tau = t - t_0$,

$$\int_{-\infty}^{\infty} x(t-t_0) e^{-j\omega t} dt = \int_{-\infty}^{\infty} x(\tau) e^{-j\omega(\tau+t_0)} d\tau$$

$$= e^{-j\omega t_0} \int_{-\infty}^{\infty} x(\tau) e^{-j\omega\tau} d\tau$$

$$= e^{-j\omega t_0} X(\omega)$$

[4]

i) Divide F[z] by z, and perform partial fraction:

$$\frac{F[z]}{z} = \frac{z-7}{z^2-5z+4} = \frac{z-7}{(z-1)(z-4)} = \frac{2}{z-1} - \frac{1}{z-4}.$$

$$F[z] = 2\frac{z}{z-1} - \frac{z}{z-4}$$

$$\therefore \; f[k] = [2-4^k]u[k].$$

[4]

j)

i) Nyquist rate is $2 \times 4.5 \times 10^6 = 9$ MHz.
Therefore the actual sampling rate = 9 MHz×1.2=10.8 MHz.

[2]

ii) 1024 levels require 10 bits per sample. Therefore bit-rate is:

$$10.8 \times 10^6 \times 10 = 108 \text{ Mbits/sec.}$$

[2]

Answer to Question 2

Express the differential equation in terms of D operators:

$$(D^2+6D+9)y(t)=(2D+9)x(t) \Rightarrow Q(D)y(t)=P(D)x(t)$$
$$Q(D)=(D^2+6D+9), \qquad P(D)=(2D+9)$$

The characteristic equation is therefore:

$$(\lambda^2+6\lambda+9)=0 \Rightarrow (\lambda+3)^2=0.$$

$$\therefore\ y_0(t)=(c_1+c_2t)e^{-3t} \quad \text{and} \quad \dot{y}_0(t)=[-3(c_1+c_2t)+c_2]e^{-3t}$$

Setting t = 0, and substituting e^{-3t} $y_0(0)=0$ and $\dot{y}_0(0)=1$, gives

$$\left.\begin{array}{r} 0=c_1 \\ 1=-3c_1+c_2 \end{array}\right\} \Rightarrow \begin{array}{l} c_1=0 \\ c_2=1 \end{array}$$

$$\therefore\ y_0(t)=te^{-3t} \quad \text{and} \quad \dot{y}_0(t)=(-3t+1)e^{-3t}$$

Now the impulse response can be calculated:

$$h(t)=[P(D)y_0(t)]u(t)$$

$$\begin{aligned} &=[2y_0(t)+9\dot{y}_0(t)]u(t) \\ &=(-6te^{-3t}+2e^{-3t}+9te^{-3t})\,u(t) \\ &=(2+3t)e^{-3t}\,u(t) \end{aligned}$$

[15]

a) The system response to $u(t)$ is $g(t)$, and the response to the step $u(t-\tau)$ is $g(t-\tau)$ (time-invariant property).

It is given that $\Delta f=\frac{\Delta f}{\Delta\tau}\Delta\tau=\dot{f}(\tau)\Delta\tau.$ The step component at $t=n\Delta\tau$ therefore has a height of $\dot{f}(n\Delta\tau)\Delta\tau$, and can be expressed as $\left[\dot{f}(n\Delta\tau)\Delta\tau\right]u(t-n\Delta\tau)$. This gives a response $\Delta y(t)$ at the output, where

$$\Delta y(t)=\left[\dot{f}(n\Delta\tau)\Delta\tau\right]g(t-n\Delta\tau).$$

Therefore, the total response due to ALL step components is:

$$\begin{aligned} y(t)&=\lim_{\Delta\tau\to 0}\sum_{n=-\infty}^{\infty}\dot{f}(n\Delta\tau)g(t-n\Delta\tau)\Delta\tau \\ &=\int_{-\infty}^{\infty}\dot{f}(\tau)g(t-\tau)\,d\tau \\ &=\dot{f}(\tau)*g(\tau) \\ &=\dot{f}(t)*g(t). \end{aligned}$$

[15]

Answer to Question 3

a) i) From definition of Fourier transform,

$$F(\omega) = \int_{-\infty}^{\infty} f(t)e^{-j\omega t}dt$$

$$= \int_{-\tau}^{0} e^{-j\omega t}dt - \int_{0}^{\tau} e^{-j\omega t}dt$$

$$= -\frac{1}{j\omega}e^{-j\omega t}\Big|_{-\tau}^{0} - \frac{1}{j\omega}e^{-j\omega t}\Big|_{0}^{\tau}$$

$$= -\frac{1}{j\omega} + \frac{1}{j\omega}e^{j\omega t} + \frac{1}{j\omega}e^{-j\omega t} - \frac{1}{j\omega}$$

$$= -\frac{2}{j\omega} + \frac{2}{j\omega}\cos\omega\tau$$

$$= j\frac{4}{\omega}\sin^2\left(\frac{\omega\tau}{2}\right)$$

[10]

ii) Express *f(t)* as sum of two rectangular functions:

$$f(t) = rect\left(\frac{t+\tau/2}{\tau}\right) - rect\left(\frac{t-\tau/2}{\tau}\right)$$

Given that

$$rect\left(\frac{t}{\tau}\right) \Leftrightarrow \tau \,\mathrm{sinc}\left(\frac{\omega\tau}{2}\right),$$

apply time-shifting property gives

$$rect\left(\frac{t \pm \tau/2}{\tau}\right) \Leftrightarrow \tau \,\mathrm{sinc}\left(\frac{\omega\tau}{2}\right)e^{\pm j\omega\tau/2}.$$

Therefore

$$F(\omega) = \tau \,\mathrm{sinc}\left(\frac{\omega\tau}{2}\right)e^{+j\omega\tau/2} - \tau \,\mathrm{sinc}\left(\frac{\omega\tau}{2}\right)e^{-j\omega\tau/2}$$

$$= 2j\,\tau \,\mathrm{sinc}\left(\frac{\omega\tau}{2}\right)\sin\left(\frac{\omega\tau}{2}\right)$$

$$= j\frac{4}{\omega}\sin^2\left(\frac{\omega\tau}{2}\right)$$

[10]

b)

$$f(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{t^2}{2\sigma^2}}$$

and $$\frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{t^2}{2\sigma^2}} \Leftrightarrow e^{-\sigma^2\omega^2/2}.$$

Parseval's Theorem states:

$$E_f = \frac{1}{2\pi}\int_{-\infty}^{\infty} \left|F(\omega)\right|^2 d\omega .$$

Given

$$F(\omega) = e^{-\sigma^2\omega^2/2}$$

we obtain:

$$E_f = \frac{1}{2\pi}\int_{-\infty}^{\infty} e^{-\sigma^2\omega^2} d\omega .$$

Let $\sigma\omega = \frac{x}{\sqrt{2}}$, then $\sigma^2\omega^2 = \frac{x^2}{2}$ and $d\omega = \frac{1}{\sigma\sqrt{2}}dx$.

Therefore

$$E_f = \frac{1}{2\pi}\frac{1}{\sigma\sqrt{2}}\int_{-\infty}^{\infty} e^{-x^2/2}dx = \frac{1}{2\sigma\sqrt{\pi}} .$$

[10]

Answer to Question 4

a) Taking z-transform of both sides:

$$zY[z]-0.5Y[z]=zF[z]+0.8F[z].$$

Therefore

$$H[z]=\frac{Y[z]}{F[z]}=\frac{z+0.8}{z-0.5}.$$

b) The frequency response is given by:

$$H[e^{j\Omega}]=\frac{e^{j\Omega}+0.8}{e^{j\Omega}-0.5}=\frac{(\cos\Omega+0.8)+j\sin\Omega}{(\cos\Omega-0.5)+j\sin\Omega}.$$

Therefore, the amplitude response is

$$\left|H[e^{j\Omega}]\right|^2=H[e^{j\Omega}]H[e^{-j\Omega}].$$

$$=\frac{(e^{j\Omega}+0.8)(e^{-j\Omega}+0.8)}{(e^{j\Omega}-0.5)(e^{-j\Omega}-0.5)}.$$

$$=\frac{1.64+1.6\cos\Omega}{1.25-\cos\Omega}$$

The phase response is

$$\angle H[e^{j\Omega}]=\tan^{-1}\left(\frac{\sin\Omega}{\cos\Omega+0.8}\right)-\tan^{-1}\left(\frac{\sin\Omega}{\cos\Omega-0.5}\right).$$

.

c) Since $f[k]=\cos(0.5k-\frac{\pi}{3})$, $\Omega=0.5$.

Therefore

$$\left|H[e^{j\Omega}]\right|^2=\frac{1.64+1.6\cos 0.5}{1.25-\cos 0.5}=8.174$$

$$\left|H[e^{j\Omega}]\right|=2.86$$

$$\angle H[e^{j\Omega}]=\tan^{-1}\left(\frac{\sin 0.5}{\cos 0.5+0.8}\right)-\tan^{-1}\left(\frac{\sin 0.5}{\cos 0.5-0.5}\right).$$

$$=0.2784-0.9037$$

$$=-0.6253 \text{ radian or } 35.83^\circ.$$

Therfore, the system response is

$$y[k]=2.86\cos(0.5k-\frac{\pi}{3}-0.6253)=2.86\cos(0.5k-1.6725).$$