ECE 401 Signal and Image Analysis
Homework 3

UNIVERSITY OF ILLINOIS
Department of Electrical and Computer Engineering

Assigned: 9/28/2022; Due: 10/5/2022
Reading: *DSP First* Chapter 5

Problem 3.1

In MP3, one of the filters you'll create is a local averaging filter. A local averaging filter produces an output $y[n]$, at time n, which is the average of the previous N samples of $x[m]$:

$$y[n] = \sum_{m=-\infty}^{\infty} h[m]x[n-m] \tag{3.1-1}$$

$$h[m] = \begin{cases} \frac{1}{N} & 0 \le m \le N-1 \\ 0 & \text{otherwise} \end{cases} \tag{3.1-2}$$

(a) First, consider what happens if $x[m]$ is a pure tone with a period of $N_0 = \frac{2\pi}{\omega_0}$, an amplitude of A, and a phase of θ:

$$x[n] = A\cos(\omega_0 n - \theta)$$

Suppose that the averaging window, N, is exactly an integer multiple of N_0. For example, suppose that $N = 3N_0$. Draw a picture of $x[n]$ as a function of n, and shade in the regions that would be added together by the summation in Eq. (3.1-1) in order to compute $y[0]$. Argue based on your figure (with no calculations at all) that $y[0] = 0$.

(b) Adding up the samples of a cosine is easy when N is an integer multiple of N_0, but hard otherwise. It's actually much easier to add the samples of a complex exponential, because we can use the standard geometric series formula (`https://en.wikipedia.org/wiki/Geometric_series#Formula`). Use that formula to find $y[N-1]$ when

$$x[n] = e^{j\omega_0 n}$$

Your result should have the form $y[0] = (1-a)/(1-b)$ for some complex-valued constants, a and b, that depend on π, N, and ω_0, but not on m or n.

Problem 3.2

Another of the filters you'll create in MP3 is a backward-difference filter. A backward-difference filter is one of several different ways of approximating a first-derivative:

$$y[n] = \sum_{m=-\infty}^{\infty} h[m]x[n-m] \tag{3.2-1}$$

$$h[m] = \begin{cases} 1 & m = 0 \\ -1 & m = 1 \\ 0 & \text{otherwise} \end{cases} \tag{3.2-2}$$

(a) First, consider what happens if $x[m]$ is a pure tone with a period of $T_0 = \frac{2\pi}{\omega_0}$, an amplitude of A, and a phase of θ:

$$x[n] = A\cos\left(\omega_0 n - \theta\right) \tag{3.2-3}$$

Plug Eq. (3.2-3) into Eq. (3.2-1), then use the following trigonometric identity and the following approximation to discover in exactly what way the first-difference operator approximates a derivative:

$$-2\sin(a)\sin(b) = \cos(a+b) - \cos(a-b)$$
$$\sin(b) \approx b \quad \text{if } b \text{ is small}$$

In order to apply the approximation, you can assume that ω_0 is a small number.

(b) Let's try the same thing with a complex exponential. Plug the following value of $x[n]$ into Eq. (3.2-1)

$$x[n] = e^{j\omega_0 n},$$

then assume that ω_0 is a small number, and simplify using the approximation

$$e^{\phi} \approx 1 + \phi \quad \text{if } \phi \text{ is small}$$

in order to get something that looks like $dx[n]/dn$.