



## Lecture 1-6: Noise and Filters

### Overview

1. **Periodic and Aperiodic Signals Review:** by **periodic** signals, we mean signals that have a waveform shape that repeats. The time taken for the waveform to repeat is its **period** (T), and the number of periods in one second is called the **repetition frequency** (or the fundamental frequency) ( $F=1/T$ ). **Aperiodic** signals do not have a repeating waveform shape: they are either signals that occur once (**impulsive** signals) or signals that change randomly (**noise** signals), see figure 1-6.1.
2. **Spectra of Periodic and Aperiodic Signals:** the spectral analysis of any periodic signal shows a **line spectrum**. The spectral components occur only at frequencies which are whole-number multiples of the repetition frequency (harmonics). The spectral analysis of any aperiodic signal shows a **continuous spectrum**. Spectral components occur at all frequencies. One explanation for this is that the repetition frequency of an aperiodic signal is zero, so the "harmonics" are 0Hz apart. The spectrum of a single narrow pulse shows the same energy at all frequencies, while the spectrum of "white" noise has the same mean energy at all frequencies. Other aperiodic signals have continuous spectra that are not flat.
3. **Time Domain and Frequency Domain processing:** we can consider how the waveform of a signal changes as it passes through a system: for example how a pulse is converted to a damped sinusoid when passed through a resonator. This looks at the **time domain** aspects of the process, see figure 1-6.2. Alternatively we can consider how the spectrum of a signal is changed as it passes through a system: for example how the spectrum of a pulse is changed to the spectrum of a damped sinusoid. This looks at **frequency domain** aspects of the process, see figure 1-6.3. In the latter case it is easy to see the role the frequency response of the system plays in shaping the signal spectrum.
4. **Frequency Response of Complex Systems:** any complex linear system can be treated as a combination of simpler systems. Specifically a complex system can always be analysed into a chain of simpler systems where the overall frequency response is simply the product of the frequency responses of the component systems (see figure 1-6.4). An important consequence of this is that the frequency response of any system can be analysed ultimately into a series of simple resonances and simple anti-resonances. (If resonances cause peaks in a response, anti-resonances cause dips).
5. **Filters:** these are a class of systems which have useful frequency response shapes. A **low-pass filter** removes all spectral components of an input signal that have frequencies higher than some cut-off frequency. A **high-pass filter** removes spectral components lower than some cut off frequency. A **band-pass filter** removes spectral components that occur at frequencies outside a given range: it only lets through components within a band of frequencies.
6. **Application of a Band-pass filter for signal analysis:** band-pass filters are particularly useful for analysing the spectral content of signals. We can use a number of band-pass filters to isolate each frequency region of the signal in turn so that we can measure the energy in each region: effectively calculating a spectrum (see figure 1-6.5)

## **Reading**

Choose at least one from:

- Rosen & Howell, Signals and Systems for Speech and Hearing (1<sup>st</sup> edition), Chapter 6: The frequency response of systems, pp75-92. *Accessible introduction to filters.*
- Rosen & Howell, Signals and Systems for Speech and Hearing (1<sup>st</sup> edition), Chapter 7: The Frequency Characterization of Signals, pp142-147. *Spectra of noise signals.*
- Rosen & Howell, Signals and Systems for Speech and Hearing (1<sup>st</sup> edition), Chapter 8: Signals through Systems. *For those wanting more.*

## **Learning Activities**

You can help yourself understand and remember this week's teaching by doing the following activities before next week:

1. Practise making sketches from memory of the spectra of various types of sound, for example: a sinewave, a pulse, a pulse-train, white noise, a vowel.
2. Explain in words supported by diagrams what happens in the time domain when a pulse-train is put through a simple resonator, then describe the event again but focussing on what happens in the frequency domain.
3. Write descriptions in your own words of what low-pass, high-pass and band-pass filters actually do to a signal.
4. Write a description of how a band-pass filter could be used to determine the amplitude and frequency of the individual harmonic components of a complex periodic tone.

If you are unsure about any of these, make sure you ask questions in the lab or in tutorial.

## **Definitions**

**Low-pass filter:** a system that reduces the amplitude of signal components that are above some cut-off frequency

**High-pass filter:** a system that reduces the amplitude of signal components that are below some cut-off frequency

**Band-pass filter:** a system that reduces the amplitude of signal components that lie outside a given frequency range.

**Narrow pulse:** an aperiodic impulsive signal that has equal amounts of energy at every frequency.

**White noise:** an aperiodic random signal that has equal average energy at every frequency.

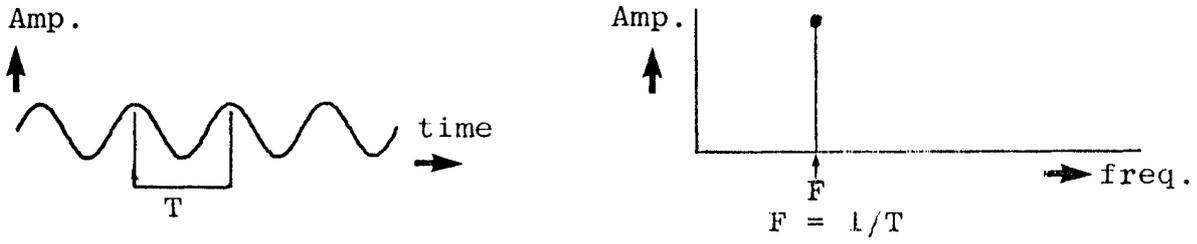
## **Reflections**

You can improve your learning by reflecting on your understanding. Here are some suggestions for questions related to this week's teaching.

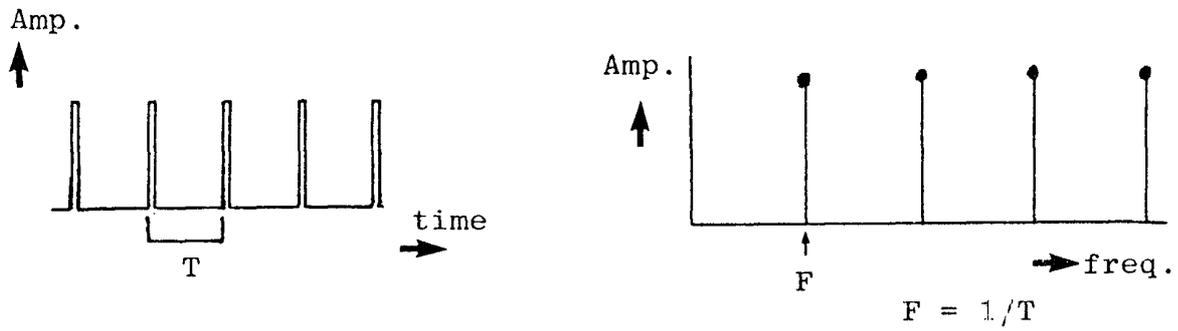
1. Think of some sources of sound and classify them as periodic, impulsive or noise.
2. Must an excised section of a periodic signal still be periodic?
3. How might you explain why the spectrum of a single narrow pulse has sinewave components at every frequency?
4. How might you explain why the spectrum of a noise signal has sinewave components at every frequency?
5. How can we calculate the overall effect of two systems if we know the frequency response of each one? What are the advantages of expressing the frequency response graphs in decibels?
6. How can we build a band-pass filter from a low-pass and a high-pass filter? Build a bandpass filter with a band from 900 to 1100Hz.
7. Explain how bandpass filters can be used to estimate the spectrum of a signal.
8. Is a narrow bandpass filter lightly damped or heavily damped?
9. Imagine a sound being generated by passing a pulse train through a simple resonator. What controls the loudness of the sound? What controls the pitch of the sound? What controls the timbre of the sound? What effect does a change in the damping of the resonator have on the sound?

**Figure 1-6.1 Summary of Waveforms and Spectra**

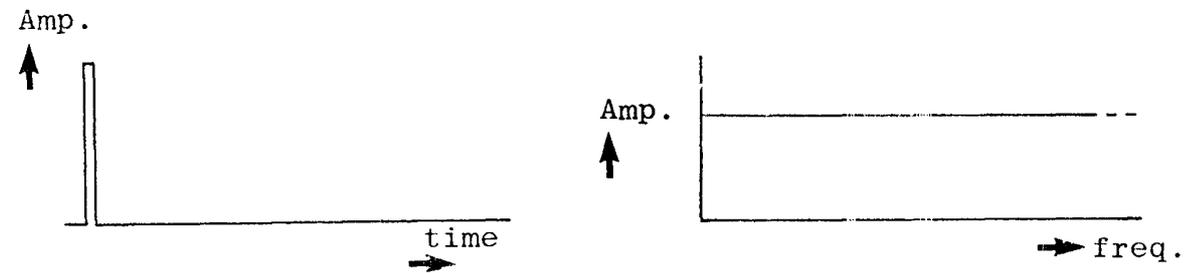
**A). Simple Periodic (i.e. sinewave)**



**B). Complex Periodic (e.g. train of narrow pulses)**



**C). Impulsive Aperiodic (e.g. single narrow pulse)**



**D). Noise Aperiodic (e.g. white noise)**

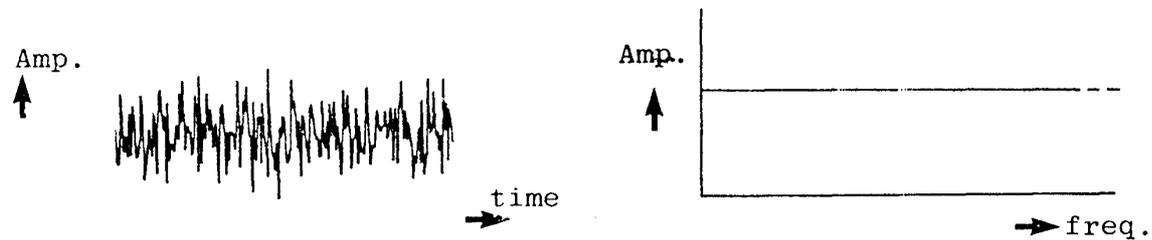
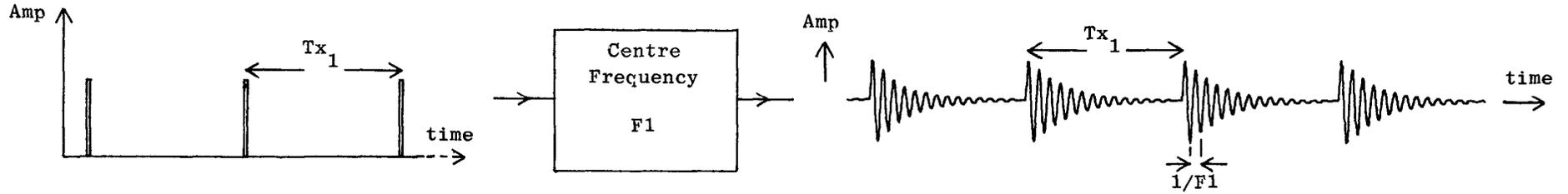
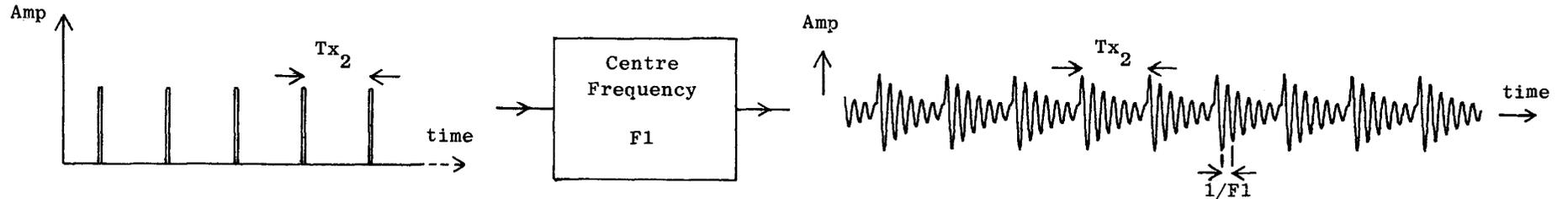


Figure 1-6.2 Excitation of a Simple Resonator - Time Description

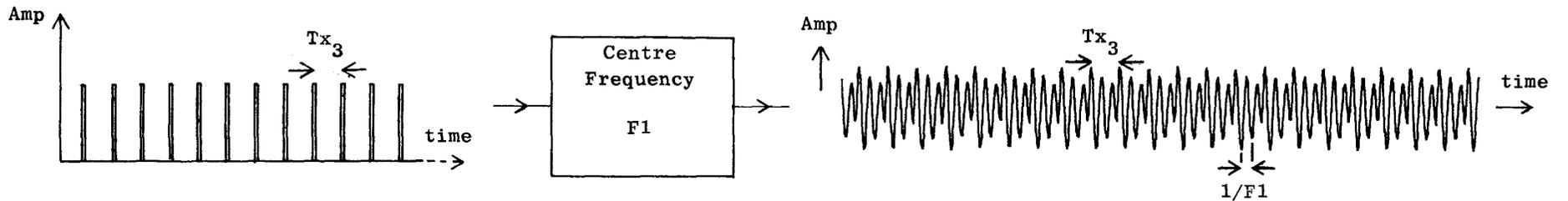
1. Low Fundamental frequency pulse train



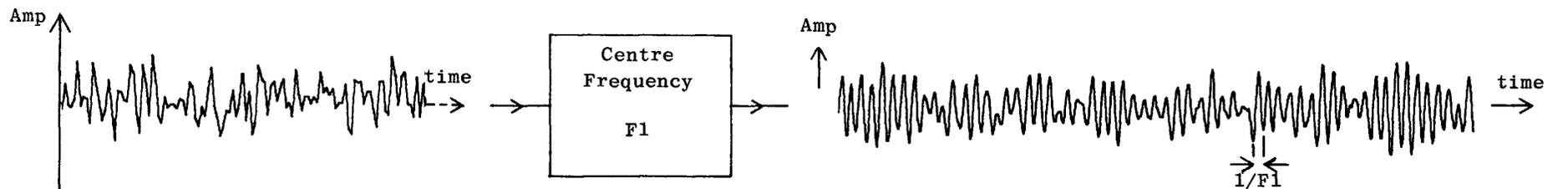
2. Mid Fundamental frequency pulse train



3. High Fundamental frequency pulse train

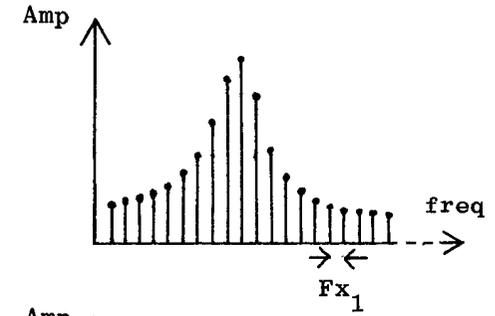
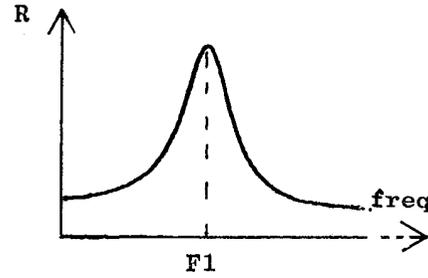
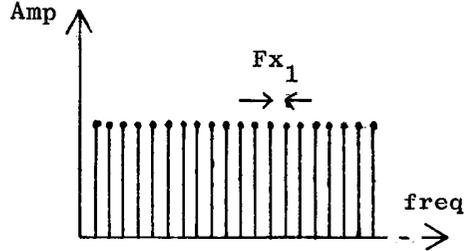


4. White noise waveform

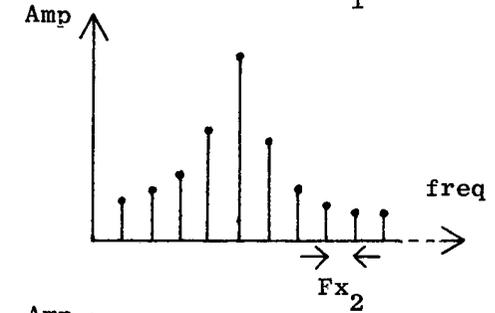
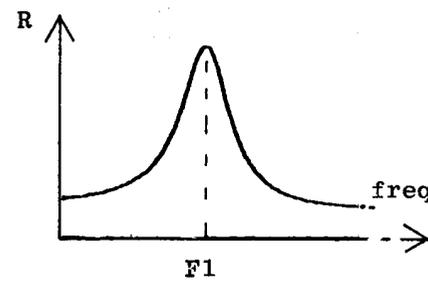
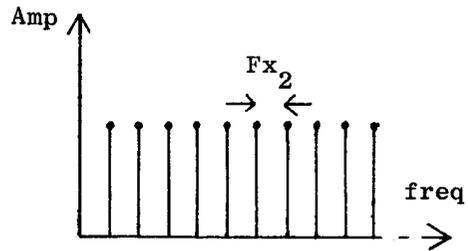


**Figure 1-6.3 Excitation of a Simple Resonator - Frequency Description**

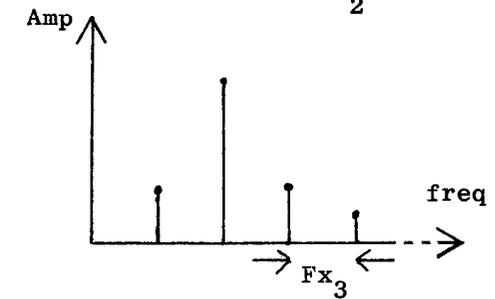
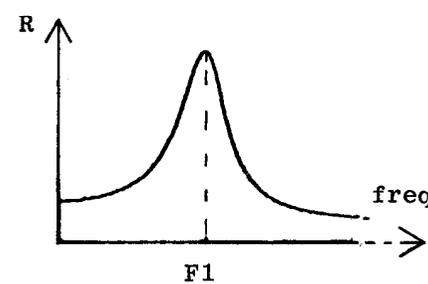
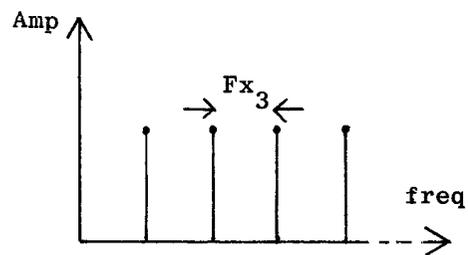
1. Low Fundamental frequency pulse train



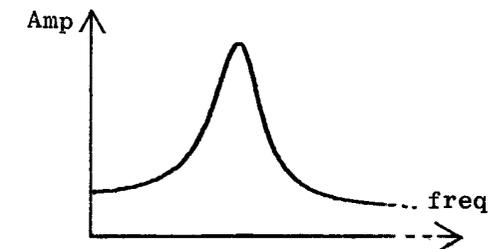
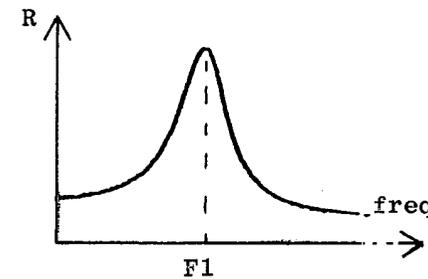
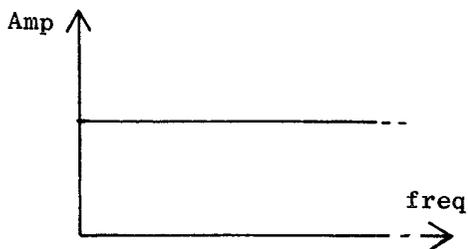
2. Mid Fundamental frequency pulse train



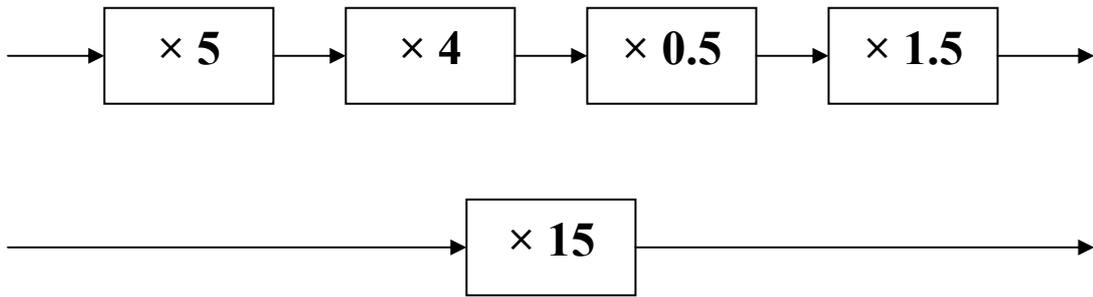
3. High Fundamental frequency pulse train



4. White noise waveform

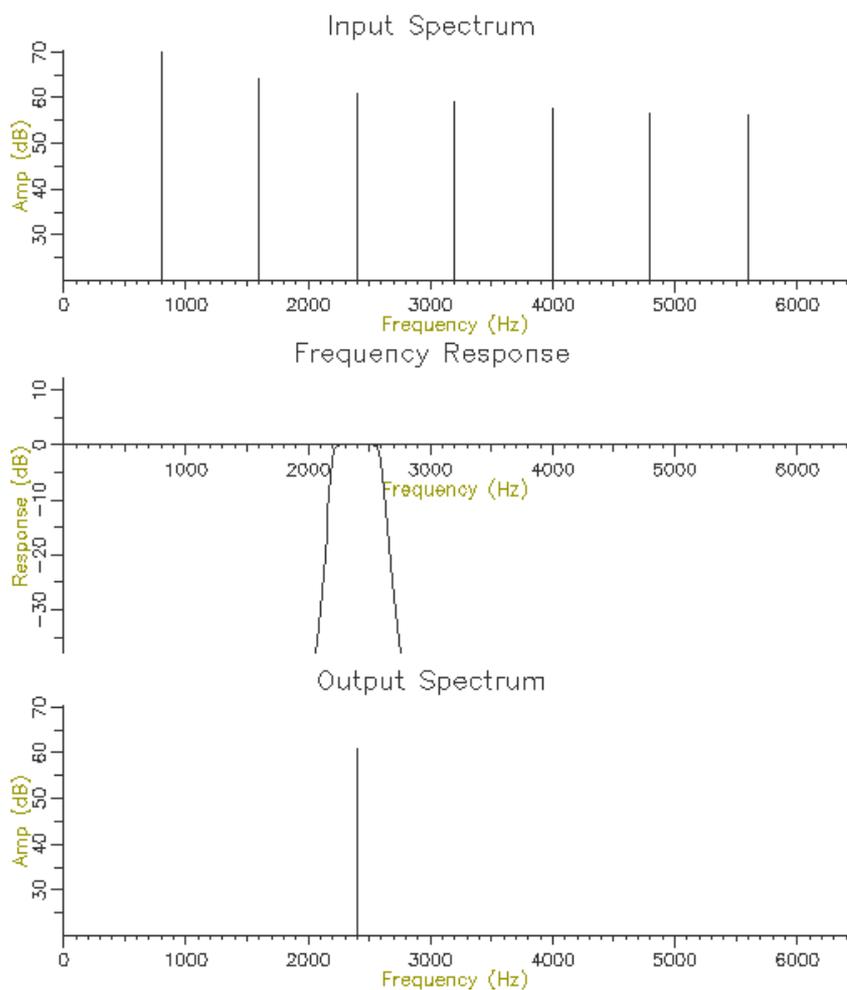


**Figure 1-6.4 Combining linear systems**



Any sequence of linear systems can be replaced by a single system whose response is the product of the individual responses.

**Figure 1-6.5 Use of a bandpass filter to analyse a signal**



Since a bandpass system only passes frequencies within a given region, we can use it to find which regions of the input signal contain frequency components.

# Lab 1-6: Signals and Systems Workbench

## Introduction

Signals and systems theory aims to give a quantitative account of how signals can be characterised and how systems that modify signals can be characterised. We have seen how the use of a spectrum graph gives us a quantitative description of which sinusoidal components are present in a signal. We have seen how a frequency response graph gives us a quantitative description of how the amplitude of a sinusoidal component of a signal is changed by its passage through a system. Together, spectrum graphs and frequency response graphs give us a powerful means for describing signals (including speech signals) and systems that process and generate signals (including the vocal tract).

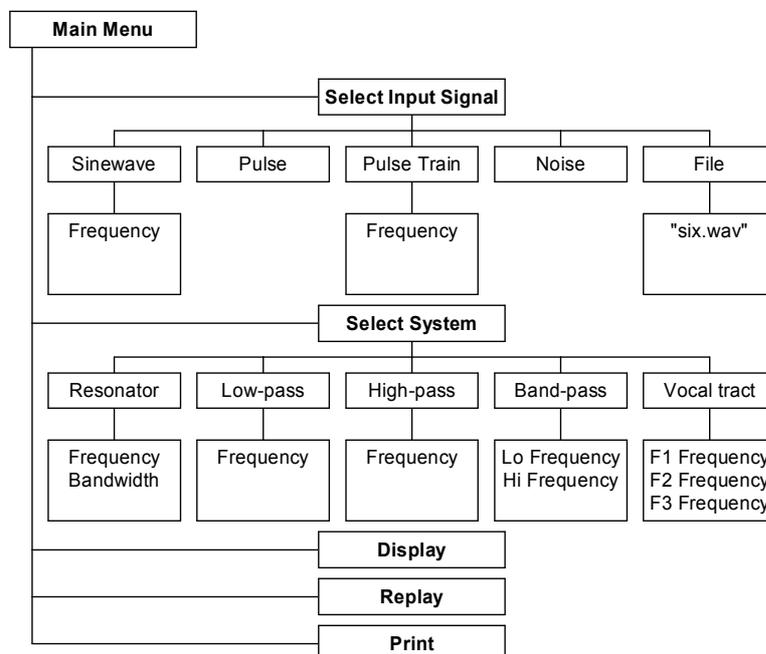
## Learning objectives

In this laboratory session we reinforce all the earlier ideas of signals and systems theory by passing a number of different signals through a number of different systems and exploring what happens in both the time domain and the frequency domain.

## Method

You are provided with a computer program Esystem that can generate a range of signals and pass them through a range of systems. The program displays the waveforms and the spectra of the signals, and it displays the frequency response of the systems. (<http://www.phon.ucl.ac.uk/resource/sfs/esystem/>).

Menu operation is as follows:



## **Observations**

Use the program to answer the questions below. Write down the answers to the questions in your notebook as you work through the activities. You can print out any picture, but be sure to enter your name as a title.

### **A. Spectra of different waveforms**

1. Set the system to be an amplifier of +6dB. What does this system do to signals passing through it?
2. What does the spectrum of a sinewave at 1000Hz look like?
3. What does the spectrum of a pulse train with a fundamental frequency of 100Hz look like? How do the input signal and input spectrum graphs change if the repetition frequency is changed to 200Hz? To 50Hz?
4. What does the spectrum of a single pulse look like? Explain this result using your answer to question 3 above.
5. What does the spectrum of white noise look like? Why do you think white noise is called “white”?

### **B. Effect of a simple resonator on a sinewave**

1. Set the system to be a simple resonator with a resonant frequency of 1000Hz and a bandwidth of 100Hz. How might you measure these numbers from the frequency response graph?
2. Pass a sinewave at 1000Hz through the resonator. Explain (numerically) what happens to the signal and its spectrum.
3. Pass a sinewave at 2000Hz through the resonator. Explain (numerically) what happens to the signal and its spectrum.
4. Set the system to be a simple resonator at 2000Hz with a bandwidth of 100Hz. Pass a 1000Hz sinewave through it. Explain (numerically) what happens to the signal and its spectrum.

### **C. Effect of a simple resonator on a pulse train**

1. Set the system to be a simple resonator at 1000Hz with a bandwidth of 100Hz. Set the input signal to be a pulse train with a fundamental frequency of 100Hz. Explain the shape of the output waveform.
2. Explain the shape of the output spectrum. Why are some harmonics amplified more than others?
3. Change the bandwidth of the resonator to 300Hz. Explain the change in the shape of the output waveform.

### **D. Effect of a simple resonator on white noise**

1. Set the system to be a simple resonator at 2500Hz with a bandwidth of 300Hz. Set the input signal to be white noise. Explain the shape of the output spectrum.
2. What speech sound has the most similar quality to this?
3. Change the resonant frequency to 4000Hz. What speech sound is most similar now?

### **E. Effect of filtering on a speech signal**

1. Set the system to be a low-pass filter at 1000Hz. What does this system do to amplitude components of the signal above 1000Hz?
2. Set the input signal to be the contents of the file "six.wav". Listen to the input and output signals. How would you describe the change in timbre caused by the filter?
3. Set the system to be a high-pass filter at 1500Hz. How has this filter affected the timbre of the signal?
4. Set the system to be a band-pass filter between 300Hz and 3500Hz. How would you describe the change in timbre now? What does this quality remind you of?

### **F. Use of band-pass filter for signal analysis**

1. Set the input signal to be a pulse train with a fundamental frequency of 200Hz. Set the system to be a band-pass filter between 950Hz and 1050Hz. What part of the input signal can be seen in the output signal?
2. Change the band-pass filter so that it is between 850Hz and 950Hz. Why is there very little energy in the output spectrum?
3. How do 1 and 2 show us how we might use band-pass filters to analyse a sound?

### **G. Making a vowel sound**

1. Set the input to be a sawtooth waveform at 125Hz. Set the system to have a vowel-like frequency response with  $F_1=500\text{Hz}$ ,  $F_2=1500\text{Hz}$ ,  $F_3=2500\text{Hz}$ . What vowel does the output sound like?
2. Draw analogies between the figure and human speech production: (i) Input Signal, (ii) System, (iii) Output Signal.

### **Concluding Remarks**

1. Why is signals and systems theory useful in analysing speech production? (Think what could be described with a spectrum or a frequency response graph)
2. Why do sinewaves have such an important role in signals and systems theory?