HLab–1 — "The Response of Systems to Special Signals"

Lab Week: Week 6
Total Marks: 10
Contribution to Final Assessment: 3%
Grading: Lab is marked based on satisfactory completion of tasks. Attendance is compulsory.
Relevant Textbook Sections: 1.6

1 Learning Outcomes

After completing this lab, the students should be able to:

- Understand how signals are distorted when the system response is affected by inertia, and to select signals suitable for system characterization.
- Demonstrate the effect of sinusoidal signals on systems response.
- Test the linearity of various practical systems.

2 Modules and Devices Needed

`Audio Oscillator`, `Sequence Generator`, `Baseband Channel Filters` (`BBCF`), `Oscilloscope`, `Buffer Amplifier`, `VCO`, and `Frequency Counter`.

3 Background

Step Response of System

The step response of a system is used to characterize, measure and specify "inertia". It can be determined as the output of a system, with zero initial conditions, when a step function (a function that changes its state from `0` to `1`) is applied. Here, we observe and investigate the step response for different systems.

Practical Considerations: From a practical point of view, knowing how the system responds to a sudden input is very important. For example, the most important consideration affecting the speed of a digital signal is the switching process to produce a change of state. The switching time can never be instantaneous in a physical system because of energy storage in electronic circuitry, cabling and connecting hardware. This energy lingers in stray capacitance and inductance, and cannot be completely eliminated in wiring and in electronic components. The effect is just like "inertia" in a mechanical system.

Impulse Response

The impulse response refers to the change in the output of the system in response to some external transient change. The impulse response of the system is its output when presented with a brief input signal, called an impulse. The impulse input is considered as an energy burst to a system. The idea is straightforward. The pulse width is reduced to an infinitesimal value while maintaining the product of amplitude and width constant. Naturally this implies a very large amplitude. The impulse function plays a central role as one of the fundamental signals in systems theory, with numerous ramifications.

It is not possible to produce a perfect impulse to serve as input for testing and therefore a short width rectangular pulse is used as an approximation of an impulse.

Linearity of a System

The system $y = S(x)$ is said to be **linear** if it satisfies the homogeneity (scaling) property

$$ay = S(ax),$$

and also satisfies the additivity property

$$y_1 + y_2 = S(x_1 + x_2),$$

where $y_1 = S(x_1)$ and $y_2 = S(x_2)$.

Practical systems have limitations like bandwidth and maximum amplitude that the output can achieve, etc. Therefore, systems may not be linear for all types of inputs. A system may treat some portion of the input of the signal or some frequency components of the system linearly.

4 Part 1: Step Response & Impulse Response of Different Systems

4.1 Introduction

We study the step and impulse responses of different systems. The audio oscillator module can generate **`TTL`** (signals that take value of 0 or 5 volts) or analog sinusoidal signals of variable frequency. The **`TIMS BBCF`** module has four different channels which are considered as four different systems.

4.2 Task 1: Channel Step Response

WARNING: Yellow sockets are analog, while red sockets are **`TTL`**. Always, make sure that the connected sockets are compatible.

1. Connect the circuit shown in *Figure 1*. Using the **`AUDIO OSCILLATOR`**, set the frequency value to minimum, by turning the knob fully counter-clockwise. Using the **`SCOPE SELECTOR`** in the bottom row of **`TIMS`**, connect the output in *Figure 1* to the oscilloscope Channel X, and the output of the **`AUDIO OSCILLATOR`** to Channel Y. Adjust the time base to display no more than two transitions. On the **`BBCF`**, select Channel 3. Observe the channel response to a single transition (you can use scope trigger and other time base controls to display a **`LO`** to **`HI`** transition). When the response to a step excitation is settled, it yields the step response.

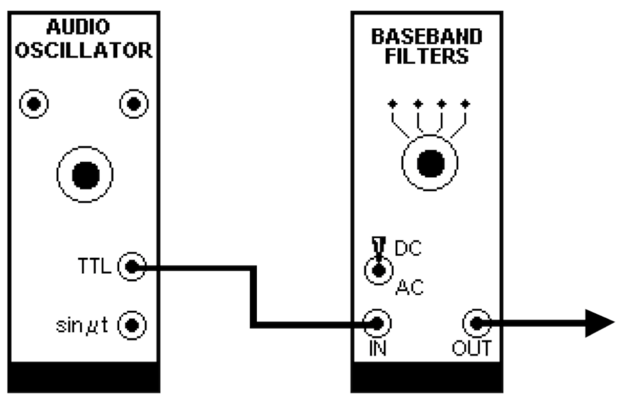

Figure 1: *Task 1: Channel Step Response*

2. Using the same setup, display the step response for Channel 2 of the **`BBCF`**. Notice the presence of oscillations and the relatively long settling time to the final value (sometimes known as ringing —— a term that goes back to the days of manual telegraphy and Morse code).
3. Now switch to Channel 4. Compare the time delay of the response with the other two channels (a convenient reference point to measure delay is the 50% amplitude). (The rise-time of the step response is an indicator of the time taken to traverse the transition range. Various definitions can be found according to the application context. We use the frequently used 90% criterion, which is the time taken by the output to reach the 90% of the steady state value.)
4. Measure and compare the rise time of the three step responses. Show your readings to the tutor.

4.3 Task 2: Channel Impulse Response

An isolated pulse can also be used as an alternative to using an isolated step as the excitation to probe the behaviour of the system. The pulse at the SYNC output of the sequence generator serves as input for this.

1. Connect the circuit in *Figure 2*. Also, connect the `TTL` output of the Audio Oscillator to the `TTL` input of the Frequency Counter in the bottom row of `TIMS`. Set the `Audio Oscillator` to `0.8 kHz`. Connect the `BBCF` input to the `Sync` output of the Sequence Generator as in *Figure 2*. Pull out the `SEQUENCE GENERATOR` and check that the on-board `DIP` switch is in correct position for a short sequence, that is, both are at the upper position. Select `BBCF` Channel 3 and display the output and input of the `BBCF` on the scope. Notice that the input consists of a periodic train of widely separated impulses. The output should appear as a fully formed delayed imitation of the input. Set the time base to display one pulse only. Set the Frequency Counter knob to `1s`, and progressively increase the Audio Oscillator frequency to `1600 Hz` and observe the effect on the pulse width and pulse interval. Note that the transitions are not affected. As you continue to increase the clock frequency, the flat top between transitions gets shorter, and ultimately disappears.
    - Record the clock frequency at which this occurs and show to the tutor at the end of this task.

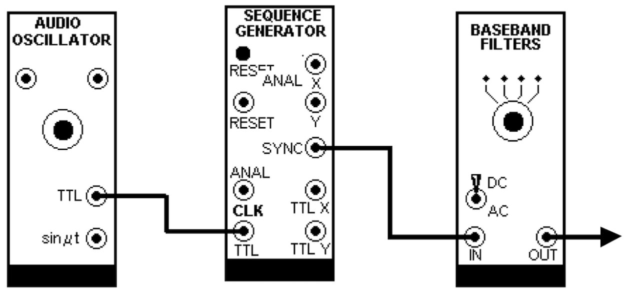

Figure 2: *Task 2: Channel Impulse Response*

2. Progressively increase the clock frequency to `2500 Hz`. Since the upgoing transition is unable to reach its final value, it is not surprising that the amplitude of the pulse gets smaller. Note the shape, and look for further changes as the clock frequency is increased over the range available on the `Audio Oscillator` (adjust the scope time base as needed).
    - Can you determine the "demarcation" pulse width, i.e., after which the response shape remains unchanging?
    - Record your observations and show at the end of this task.

Summary: You have demonstrated that, provided the time span of the excitation signal is sufficiently concentrated, the shape of the response pulse is entirely determined by the characteristics of the system. This means that the practical systems have a limit to respond to the instantaneous change at the input. If the change occurs beyond that limit, the shape of the response of the system stays the same. For example, consider the systems: the striking of a bell or tuning fork with instantaneous inputs. After the certain limit on the energy of the input, it doesn't matter how fast you strike the bell, you would hear the same sound with the change in amplitude only.

In the above exploration we also discovered practical conditions that make it possible to generate a system's natural response or characteristic which is not affected by the exact shape of the input excitation. Concurrently we have discovered a path to the definition of the impulse function and a vital bridge to link this mathematical abstraction to the world of physical signals.

5 Part 2: The Response of a System to the Sinusoidal Input

Sinusoidal signals are encountered in a large number of applications. We carry out some basic observations and compare the sinusoidal signal response of **BBCF** Channel 3 with the impulse response obtained above.

5.1 Task 3: Channel Sinusoidal Response

1. Connect the **BBCF** input to a yellow output socket on the **AUDIO OSCILLATOR** (*Figure 3*). Select Channel 3. Starting at a low frequency, display the **BBCF** output and the input. Progressively increase the frequency over the available range and observe the effect on the amplitude of the output signal. Make a record of your findings in the form of a graph of amplitude vs frequency. Consider the possible advantage of using log scales.
2. Return to the observations you recorded in Task 2. A physical mechanism was proposed there to explain the reduction in pulse response amplitude as the width of the input pulse was progressively made smaller. Consider whether the reduction in output amplitude of the sinusoidal signal with increasing frequency could be explained through a parallel argument.

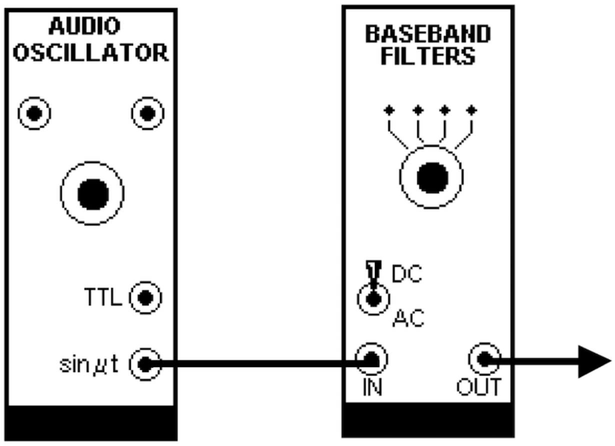

Figure 3: *Task 3: Channel Sinusoidal Response*

6 Part 3: Linearity Test for Practical Systems

We test the linearity of the following practical systems: comparator, rectifier and voltage controlled oscillator (**VCO**). That is we test whether these systems satisfy the equations (1) and (2).

Note that the application of the additivity test is not needed when the homogeneity test has failed. A complication with the additivity test is the need for replicas of the system under test, hence the homogeneity test is normally applied first.

6.1 Task 4: Comparator

1. Patch up the modules as in *Figure 4*. In addition, connect the Ref (top) input of the Comparator to the **TIMS** ground socket (Green on **VARIABLE DC**). Adjust the gain of the **Buffer Amplifier** for a 4 Volt p-p output. Adjust the scope controls for a suitable display. T une the **AUDIO OSCILLATOR** to 3 kHz initially. Try other frequencies. Show that the Comparator system does not satisfy the scaling test for linearity. Explain to the tutor.
2. A neat method to produce the output vs input graph is to use the x-y mode on your scope (refer to *Figure 4*).
3. Unlike the **BBCF** channels, investigated in Tasks 1, 2 and 3, the responses of the above system appear as effectively instantaneous, i.e., the systems are memoryless over the time scales of interest above. However, closer examination with the scope time base in the nanosecond ranges reveals that the responses are not as instantaneous as might seem. Thus the idea of a memoryless system is only relative in a theoretical context. In order to observe this: connect a 100 kHz sine-wave (from **MASTER SIGNALS**) to the **COMPARATOR** input. Measure the switching time of the output square wave.

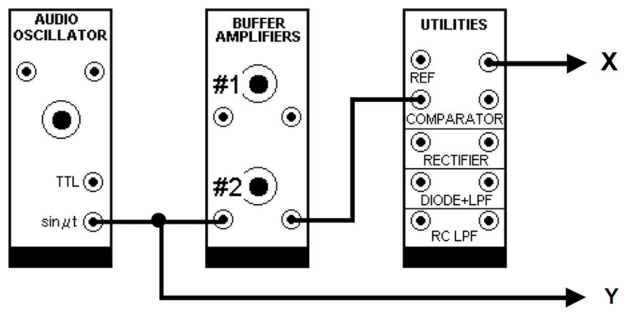

Figure 4: *Task 4: Comparator*

6.2 Task 5: Rectifier

1. Repeat the above task with the **HALFWAVE RECTIFIER** in the **UTILITIES** module and patch up the modules according to *Figure 5*. Show that this system satisfies the homogeneity test over part of the input range (i.e., where the range excludes the zero input point).
2. Observe the effect of changing the **BUFFER AMPLIFIER** gain. Record your findings concerning linearity and show to the tutor.

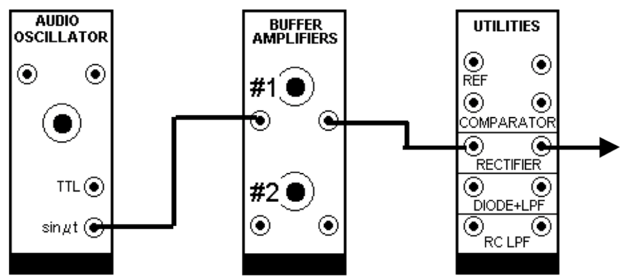

Figure 5: *Task 5: Rectifier*

6.3 Task 6: Voltage Controlled Oscillator (VCO)

1. Connect the circuit according to *Figure 6*. Set on-board switch of the **VCO** to **LO** range.
2. Connect **VARIABLE DC** to the **VCO** input. Set **DC** control to 12 o'clock. Connect the **VCO TTL** output to the **FREQUENCY COUNTER**. Set the **VCO GAIN** to 10 o'clock position and the **VCO** f0 control to 2 kHz (on the **FREQUENCY COUNTER**).
3. Observe the effect of varying the DC input voltage. Plot output frequency vs input DC voltage. (The scope can be used to measure the DC voltage).
4. Verify whether the **VCO** is a linear system, i.e., in terms of output frequency f vs input **DC** voltage V. For this purpose you should focus on incremental frequency rather than absolute frequency (obtain the plot of $\Delta f / \Delta V$). Identify the ranges of input **DC** voltage over which the system is linear. Explain to the tutor.

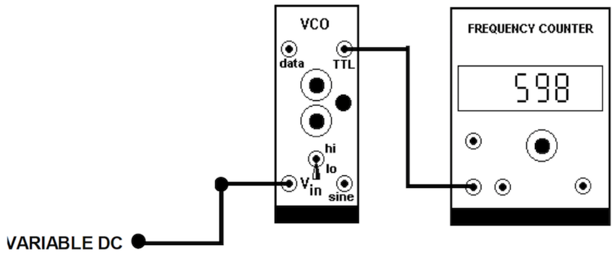

Figure 6: *Task 6: Voltage Controlled Oscillator*