EET 223
RF COMMUNICATIONS
LABORATORY EXPERIMENTS

Experimental Goals

A good technician needs to make accurate measurements, keep good records and know the proper usage and limitations of the instruments that are used.

In introductory EET courses, students are typically introduced to relatively low frequency circuits. The analog circuits focus mainly on amplifiers and filters that operate in the linear region of devices. Devices used in digital circuits operate non-linearly, but in cut-off or saturation only.

EET 223, RF Communications, introduces new concepts and measurement challenges. Analog circuits that operate non-linearly in the active region will be used to modulate, demodulate and change frequency. Instruments will be used in ways that the student may not have already experienced. Problems associated with systems working at ultra high frequencies (UHF) will also be investigated.

Some special goals of the experiments in this course are listed below.
1) To investigate the effects of noise in circuits
2) To understand aliasing errors that can occur using a sampling oscilloscope
3) To learn to use the function generator for AM, FM and Noise signals
4) To understand the difference between linear and non-linear mixing
5) To investigate requirements for modulation and demodulation
6) To test amplifiers used for power efficiency and frequency multiplication
7) To explore the use of automatic gain control (AGC) in amplifiers
8) To investigate the effects of reflections and standing waves in cables
9) To investigate propagation and reception of UHF electromagnetic energy

Contents of Experiments

Experiment No. 1        Lab Orientation and Noise Principles
Experiment No. 2        Signal Mixing and Amplitude Modulation
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Experiment No. 5        Class C Amplifiers and Frequency Multiplication
Experiment No. 6        Transmission Lines and Time Domain Reflectometry
Experiment No. 7        Antenna Measurements at Ultra High Frequencies

Each experiment will have a Pre-Lab. The Pre-Labs are informational and although they follow the procedures in the experiment, they are to be completed without going to the laboratory. There are questions given in the Pre-Labs, and answers are to be submitted to your lab instructor before the experimental procedure is performed.
Experiment No. 1
Pre-Lab
Lab Orientation and Noise Principles

The function generators in our laboratory produce other signals in addition to the standard sine, square and triangle waves of basic function generators. These include amplitude modulated (AM) as well as frequency modulated (FM) and noise signals.

The laboratory oscilloscopes are digital sampling scopes that sample and store the signals that are measured. Because of practical limits to the rate at which samples are taken, measurement errors due to a phenomenon called aliasing can occur. The stored information also enables various signal conditioning and mathematical operations to be performed by the oscilloscope. One of these operations, called the FFT or Fast Fourier Transform, allows you to determine the frequency content in signals.

Part A: Background Noise

Objective: To investigate background noise in measurements

Background noise due to external electromagnetic interference or internal electrical components can reduce the effectiveness of communication receivers. Noise, both external and internal, is critical in determining the performance of a communication receiver. Signal levels decrease with distance from a transmitter. Therefore, noise sets a limit on communication distance since the signal must be recognizable within the noise.

Consider the two images that follow. The first picture shows a small amplitude signal superimposed on white noise. The second picture shows a much larger signal with the same noise. It should be clear that in the second case it would be much easier for a receiver to recognize the signal without interference from the noise. Note that the signal and noise are superimposed in the pictures. In reality they would be combined in an additive way such that the noise would rise up and down with the signal changes.

QuickTime™ and a decompressor are needed to see this picture.

Small Signal with Noise
In the experiment, you will view the noise that is present inside the lab when a cable is connected to the oscilloscope. The cable will have open wires or clip leads at the other end. The open cable acts like a radio antenna, and the noise you will see is called electromagnetic "pickup”. The noise represents electrical signals that radiate from lights and instruments in the laboratory as well as signals radiating from locations outside the lab. It will look random, but a 60 Hz signal will also be present due to AC power currents in the laboratory. The levels are relatively large unless low resistances are connected to the cable.

The vertical controls of the oscilloscope have a BW limit function that reduces the oscilloscope bandwidth from 70 MHz to 20 MHz. This will not affect the 60 Hz but you should see a reduction in the other noise level because noise frequencies above 20 MHz have been removed. On the most sensitive vertical scale (2 mV/div) the bandwidth is automatically limited to 20 MHz so you are unable to change bandwidth.

In the experiment you will measure background noise levels with and without the bandwidth limit function enabled. The noise will probably appear something like the figure below, although it will most likely be combined with a significantly large 60Hz noise signal.
In the figure above, the lines marked \textit{min} indicate the minimum peak-to-peak noise level and the lines marked \textit{max} indicate the maximum peak-to-peak noise level. The lines marked \textit{ave} are an average of the maximum and minimum levels.

\textbf{Q1. If the maximum and minimum peak-to-peak voltages in the figure above were 10 volts and 6 volts respectively, calculate the average peak-to-peak noise amplitude.}

If a sinusoidal signal were added to noise, the noise would vary up and down in a sinusoidal pattern at the signal frequency. In the figure below the blue trace shows a sinusoidal signal plus noise. The red trace is the signal without the noise.

Notice that the signal portion is a line through the average of the higher frequency blue trace, which is the signal plus noise.

\textbf{Q2. Determine the peak-to-peak amplitude of the sinusoidal signal shown in the figure above.}

\textbf{Q3. Estimate the average peak-to-peak amplitude of the noise without the signal.}

\textbf{Part B: Noise Spectrum}

Objective: To observe the spectrum of function generator noise
The noise produced by the function generator is pseudo-random noise with a normal (Gaussian) distribution of amplitudes that are uniformly distributed in frequency up to 10 MHz. Beyond 10MHz the amplitude drops abruptly. Gaussian noise has amplitudes that vary with time according to the Gaussian probability distribution. Pseudo-random noise is not entirely random since it is generated using a computer algorithm. Nevertheless it is adequate for simulating the actual noise seen in electronic systems.

Random noise that contains all frequencies in equal proportion is called white noise. White noise is as if you took sinusoidal signals of all frequencies and phases and added them together. A filter can be used to remove certain noise frequencies resulting in a reduction of the overall amplitude of the noise. The function generator noise should look similar to the background noise you saw in the figure above except that there will be no 60 Hz portion.

When you push the Math button and select FFT with the Operation button you will be able to view the spectrum of the noise. The spectrum shows the frequency content of the signal. It will appear random as before but you will be looking at the amplitude of the noise as a function of frequency rather than time. A sample noise spectrum is shown in the figure below.

The display will have a dB vertical scale with the top level at 0 dBv. The Vertical Scale and the Horizontal Scale controls will adjust the dB/div scale and the frequency/div scale respectively. The scale values are read at the bottom of the screen. For most horizontal scale settings you will see approximately the same amplitude at all frequencies since the function generator is producing white noise. However, with the horizontal scale set to 2 MHz/div or higher you will be able to see the amplitude drop off above 10MHz.
Q4. Using the sample noise spectrum shown in the figure above, estimate the approximate frequency where the average noise amplitude drops off.

Part C: Noise and Bandwidth

Objective: To verify the effects of bandwidth on white noise:

The bandwidth of a receiver has a significant effect on reducing the noise in the system. If you increase the system bandwidth you are allowing more of the noise frequencies into the system, so you should expect to see a larger noise voltage. Thermal noise is an example of white noise. The RMS voltage of thermal noise generated by a resistor in a system that is impedance matched is given by the equation,

\[ e_n = \sqrt{4kT\Delta fR} \]

- \( k \): Boltzman’s constant \((1.38\times10^{-23} \text{ J/K})\)
- \( T \): temperature of resistor (K)
- \( \Delta f \): bandwidth of system (Hz)
- \( R \): resistance of resistor generating thermal noise (Ω)

At room temperature, \( 4kT = (1.60)(10^{-20}) \text{ Joules} \)

Resistor thermal noise is too small to be measured in our laboratory situation. Instead the function generator will used to demonstrate the affects of bandwidth on noise. It will have the same statistical characteristics as thermal white noise except it has an upper frequency limit of 10 MHz.

From the equation for resistor thermal noise voltage it can be seen that the noise voltage level is proportional to the square root of the system bandwidth. As the system bandwidth is decreased, the noise voltage will also decrease. But the noise voltage decrease will be proportional to the square root of the bandwidth decrease.

\[ \frac{e_{\text{new}}}{e_{\text{orig}}} = \sqrt{\frac{4kT\Delta f_{\text{new}}R}{4kT\Delta f_{\text{orig}}R}} = \sqrt{\frac{4kT\Delta fR}{4kT\Delta fR}} = \sqrt{x} \]

A factor \( x \) change for the system bandwidth will cause a \( \sqrt{x} \) change for the noise voltage.

You will construct an RC low-pass filter and measure the filtered output noise voltage at a starting cut-off frequency that will be called \( \Delta f_{\text{orig}} \). The measurement will be repeated at two smaller cut-off frequencies (\( \Delta f_{\text{new}} \)) and the noise voltage decrease will be compared to the bandwidth decrease as shown in the demonstration above.
Since the response of an RC low pass begins at zero Hz, the bandwidth ($\Delta f$) of the filter is the same as the cut-off frequency $f_{3\text{dB}}$.

Remember that in calculating the cutoff frequency the function generator has a 50Ω output resistance that will add to the circuit resistance.

Q5. Calculate the cut-off (-3dB) frequency of a low pass RC filter with $R=1\text{k}\Omega$ and $C=3.3\text{\mu F}$.

Q6. Calculate the effective bandwidth for this filter. (See footnote #1)

**Part D: Aliasing with the TDS202C Oscilloscope**

Objective: To investigate the effects of aliasing on signal acquisition

Unlike a traditional oscilloscope that produces a continuous display of the measured signal, a digital oscilloscope samples the signal at discrete instants in time. It converts each sample into a digital value and stores the result. In order to measure accurately it must sample at a rate that is greater than twice any frequency in the signal. Complex waveforms are composed of many harmonic frequencies, so the sample rate must be more than twice the highest harmonic frequency of the signal.

The scope normally acquires 250 samples per division or a total of 2500 samples per sweep. The sample rate depends on the sweep rate selected. At the lowest sweep rate (50 s/div) the sample rate is 5 samples per second. The sample rate increases proportionately as the sweep rate is increased to a maximum of $1 \times 10^9$ samples per second at a sweep rate of 100 ns/div. At faster sweep rates the sample rate remains $1 \times 10^9$ samples per second, so that less than 2500 samples per sweep are acquired. The missing samples are supplemented by interpolating between samples. See footnote #2.

The function generator and oscilloscope will be initially set to view only a few cycles of an input sinusoidal signal. There will be no aliasing because the sample rate for this display will be many times the frequency of the function generator. The sweep rate will be reduced so that more and more cycles of the input will appear. This will cause the sampling rate to decrease accordingly until aliasing begins. Aliasing will cause the display to show an incorrect frequency.

The aliased frequency can be calculated by taking the difference between the sample frequency and the actual signal frequency. If the function generator frequency was set to 250kHz and the sweep rate was set to 1 ms/div there would only be one sample per input cycle. That is because for a sweep rate of 1 ms/div, the sample rate is $250 \times 10^3$ samples per second, exactly the same frequency as the function generator. The aliased frequency would be zero or dc and you would see a horizontal line on the oscilloscope screen rather than the function generator signal.
You will vary the function generator frequency a small amount around 250kHz with an oscilloscope sweep rate of 1 ms/div. You will see a sinusoidal signal, but the frequency displayed and measured will be the aliased frequency rather than the function generator frequency.

**Q7. If the function generator frequency is 251kHz and the oscilloscope sweep rate is 1ms/div, calculate the frequency displayed on the oscilloscope screen.**

Next you will set the oscilloscope to the Math/FFT function and view the spectrum of the function generator signal. Since the signal is sinusoidal you should see only one vertical line representing the frequency of the signal. The horizontal scale will read Hz/div as well as samples per second. When aliasing occurs, the frequency displayed will read the aliased frequency rather than the actual frequency. When the function generator frequency is increased the displayed frequency will decrease rather than increase. The actual function generator frequency is being aliased into a lower frequency.

**Q8. If the function generator frequency is increased from 251kHz to 253kHz and the oscilloscope sweep rate is 1ms/div, how will the displayed frequency change.**

If the oscilloscope is used properly, aliasing is unlikely to occur. However, you should be aware that improper selection of the sweep rate can cause errors. You should also remember that non-sinusoidal signals have harmonics. Aliasing in a non-sinusoidal signal will also cause distortion since the harmonics will no longer be at integral multiples of each other. Also the harmonics may be several times larger than the fundamental frequency. The sample rate must be more than twice the largest harmonic frequency to prevent aliasing errors. Low pass filtering is often used to eliminate harmonics that would cause aliasing. In fact the oscilloscope has a low pass filter set to 70 MHz (or 20 MHz in the band limit mode) with a 6dB/decade roll off.

**Footnotes**

1. The frequency response curve of an RC filter has a gradual roll off instead of an abrupt drop off at the -3dB cutoff frequency. The effective bandwidth representing an ideal low pass filter would be \( \Delta f_{\text{eff}} = (\pi/2)f_{\text{3dB}} \). There is no need to use the conversion since the constant \( \pi/2 \) is the same for all bandwidths and will cancel when the comparisons are made.

2. There are three different sampling modes. In the **Sample Mode** (default mode), one sample is taken each sample period. In the **Peak Detect Mode** two samples, the maximum and the minimum values during the sample period are taken. The **Average Mode** takes an average of 4,16,64 or 128 Sample Mode acquisitions. At a sweep rate of 2.5 ms/div or slower the default or Sample Mode is automatically selected.