Unit 11: Frequency Spectral Analysis

In many areas of electronics the analysis of signal frequency spectra is very important. All the phasor algebra techniques you learned in CETT1403 are useful for only single-frequency sinusoids. TV video signals occupy about 6 MHz of bandwidth and it is useful to be able to see how a circuit may alter the TV signal by attenuating some, but not all, of the frequency spectrum of the signal. While spectrum observation is especially true in communications, it is also true in control systems, audio, and diagnostic systems. An acoustic frequency spectrum of an automobile engine can give clues as to the condition of engine valves, bearings, and even gaskets.

A spectrum analyzer is a powerful tool for displaying the frequency content of a signal. Early spectrum analyzers scanned a range of frequencies with a narrow-band filter and plotted the magnitude of the filter output as a function of frequency. To scan a wide frequency range with a narrow pass-band required a long time, but the narrower the pass-band, the better the instrument could separate two signals close in frequency. Signals of 1.0 MHz and 1.1 MHz would both fit into a 100kHz pass-band, but a 25kHz pass-band would display first one signal, and then the other, clearly separating them as the filter center frequency were tuned from 500kHz to 2.5MHz. Narrow pass-bands give higher spectral resolution. If two signals are closer together than the filter bandwidth, the display will not show two distinct peaks.

Two Signals – Poor Resolution                      Two Signals – Good Resolution

In the diagram below, you can see that the display is like an oscilloscope, but the horizontal sweep represents frequency, not time, and the vertical signal is “detected,” that is only its magnitude is displayed, not the actual ac signal.

Figure 1. Components of a spectrum analyzer.
**Frequency Heterodyne**

If you remember your trigonometric identities (and even if you don’t you can revisit them) you may remember that \( \sin(\omega_1 t) \cos(\omega_2 t) = \frac{\sin(\omega_1 + \omega_2)t}{2} + \frac{\sin(\omega_1 - \omega_2)t}{2} \). This identity enables us to see that if I multiply two sinusoids together, the result can be represented as two different sinusoids; one at the sum of the two frequencies, and the other at the difference of the two frequencies. Years ago engineers saw this as a way of greatly improving radios.

![Diagram of a Frequency Heterodyne receiver](image)

**Figure 2.**
The big advantage of heterodyne receivers is:

1) the intermediate frequency (IF) filter has a much lower center frequency than the RF signal frequency, \( f_{IN} \), making narrowband designs easier;

2) the IF filter center frequency is fixed; it never changes. Instead, the filter input signal frequency changes with tuning of the local oscillator frequency, \( f_{LO} \).

For example:

For AM radio, the standard IF is at 455kHz. AM stations have frequencies between 540kHz and 1600kHz. If the local oscillator (LO) frequency is 995kHz, and the LO sinusoid multiplies an input radio signal at 540kHz then the two outputs of the mixer are:

\( (995-540)kHz \) and \( (995+540)kHz \) or 455kHz and 1535kHz

The narrowband IF filter passes only the 455kHz signal and rejects the 1535kHz signal.

For \( f_{IN} = 1000kHz \) and an LO of 1455kHz, we have \( (1455-1000)kHz \) and \( (1455+1000)kHz \) or 455kHz and 2455kHz. Again the 455kHz signal is passed and the other is rejected by the IF filter. For the two examples, the LO frequency is changed from 995kHz to 1455kHz but the heterodyned signal stays at 455kHz.

What is the LO frequency would tune an AM station at 1600kHz? \( 2055kHz \)

There is one more aspect of heterodyne receivers you need to know. An LO of 995kHz tunes a 540kHz station as seen above, but it also would tune a 1400kHz station. After all, the sum and difference would be 995 + 1400 and 995 – 1400. The negative difference frequency, \(-455kHz\), may puzzle you, but it is real (negative frequency implies the phasor is rotating CCW). A station at 1400kHz would interfere with the desired station at 540kHz. A tunable filter is built into the RF preamplifier to get rid of high-side image frequencies.

For FM stations in the 87.9 – 107.9MHz range, the standard IF frequency is 10.7MHz. Manufacturers supply very high Q, 10.7MHz resonators (filters) for FM radios at low cost. Some FM radios do not have good image rejection and you can hear aircraft radio communications if you are driving near an airport. The aircraft band is located above the commercial FM band and aircraft use FM communications.
Heterodyne technique is used in analog spectrum analyzers instead of tunable filters. This greatly reduces cost and complexity. Instead of sweeping a narrowband filter across a band of frequencies, the LO frequency is swept instead to heterodyne signal energy into a hi-Q IF filter.

**Digital Spectrum Analyzers**

With the switch to digital instruments, spectrum analyzers became more like digital storage oscilloscopes in that they take in sample records. Most low frequency to mid-frequency range spectrum analyzers today take in a set of waveform samples just like a DSO and perform a processing algorithm on them called a discrete Fourier transform, DFT (or perhaps a fast-Fourier transform, FFT). These amazing techniques produce a display of the frequency spectrum of the sampled signal purely by computation.

The DFT technique is used in Multisim for its spectrum analyzer simulation. With digital processing, you don’t have to wait for the slow sweep of a filter, but you still have to wait for high spectral resolution since the very narrow band digital filters require far more time to process than wide band filters.

Most spectrum analyzers have the same controls that the Multisim analyzer has:

**Span Control** – It is slow and inefficient to try to see more than you need. You can set total span plus center frequency and press the ENTER button on the instrument, OR you can set the start and stop frequencies and press the ENTER button.

**Amplitude** – The amplitude buttons allow you to select between a log or linear vertical display. The dB displays permit further selection of scale (dB/div.) and reference (top-of-display value).

**Resolution** – This very important parameter determines how long the instrument needs to get enough data to make a measurement. Low resolution measurements can be made fairly quickly, while choosing narrow resolution bandwidths to separate close signals can require several minutes. Resolution should be set no wider than half the minimum signal separation. Sinusoids at 155 kHz and 170 kHz call for a resolution of no more than 7.5 kHz.

![Figure 3. Spectrum of 5 kHz square wave.](image)

Only pure sinusoids have energy at a single frequency. Figure 3 shows part of a spectrum for a 5kHz square wave. Square waves have strong odd-harmonics so line spectra are seen at 15 kHz, 25 kHz, and 35 kHz, and there are others at higher odd-harmonic frequencies.
When a pure sinusoid is distorted, waveform energy is spread to higher harmonics of the sinusoid frequency. A harmonic analyzer can measure distortion by measuring harmonic energy. A spectrum analyzer is very useful in determining the quality of a system since spectral smearing always indicates distortion. This is very important in high-performance communication circuits.

**Resolution and Sweep Speed Issues**

The signal detectors used in spectral analysis are like rectifier circuits with filters. They produce a voltage proportional to the envelope of the signal at the output of the IF filter. If the signal is being swept through the IF filter passband, the energy in the passband rises, peaks, and falls as the signal sweeps through. If the signal is not in the center of the passband, it may still have some energy in the passband, but it will be greatly attenuated by the filter band edge response. It is important that the signal sweep speed is low enough for the bandwidth of the filter to handle the sudden rise in energy as the signal sweeps through. In the old analyzers, it was possible to set sweep speed and resolution bandwidth (IF bandwidth) separately so that the sweep speed exceeded the response time of the resolution bandwidth. Sometimes the sweep speed was so slow that you needed a Polaroid camera to even see the plot because the image would fade before the sweep was complete. For very narrow bandwidths, sweep speeds had to be quite slow so that measurements took a long time. With digital Fourier Transform analyzers, the narrower the resolution, the longer the time record required, so it still takes longer to obtain the data. However, it is worth the wait. Good resolution (narrow resolution bandwidth) permits observation of spectrum details that cannot be seen in low resolution plots.

**Spectrum Analyzer Display**

Beam movement across CRT follows frequency sweep of LO so that horizontal distance = frequency. Low frequency on the left and high frequency on the right. Amplitude is usually in decibels.

**Figure 4. Plot of Swept LO Frequency Spectrum analyzer**

Narrowband signals, like single frequency sinusoids, always show up as the resolution filter response curve since the signal energy “illuminates” the filter response as the signal sweeps by.