Chapter 3: Amplitude Modulation

Chapter 3 Objectives

At the conclusion of this chapter, the reader will be able to:

- Explain conceptually how an AM signal is created.
- Use an oscilloscope to measure the percentage of modulation of an AM signal.
- Predict the frequency-domain characteristics of simple AM signals.
- Measure the various parameters of an AM signal using a spectrum analyzer.

Of all the methods of impressing information onto a carrier signal, AM is the oldest. It dates back to the beginning of radio. Although it’s old technology, it is still widely used in the following applications:

- Local broadcast (535 - 1620 kHz in the USA)
- Aircraft communications in the 118-138 MHz band.
- Short wave broadcasts in the HF bands (3-30 MHz), which affords worldwide coverage.
- Analog television, in which an AM carrier is used for the picture, and a separate FM carrier frequency is used to carry the sound.
- Data communications, in which AM and PM (Phase Modulation) are used together in high-speed modems, the subject of a later chapter.

With all of these applications (and more), "Ancient Modulation" is hardly obsolete technology. AM is an electronic fundamental!

3-1 Generating an AM Signal

As you recall, radio uses a high-frequency sine wave called a carrier to move information from the transmitter to the receiver. Intelligence can be impressed onto a carrier signal in three ways:

- Amplitude Modulation (AM): The amplitude or strength of the carrier signal is changed in step with the information. (In place of the word amplitude we can substitute voltage, power, or current.)
- Frequency Modulation (PM): The frequency of the carrier is changed with the intelligence signal. The frequency changes are normally small and hard to see on an oscilloscope (but you probably already guessed, they are easy to see on a spectrum analyzer!)
- Phase Modulation (PM): The phase angle of the carrier signal is changed to convey the information. PM is very similar to FM, and is very hard to observe accurately on an oscilloscope.

Figure 3-1 shows two carrier signals that have been modulated by the same information signal. Note how the shape of the AM signal is quite distinctive. The information is actually contained in this shape.
In contrast, the FM signal looks like a solid horizontal band. You really can't see much here at all! In fact, when the carrier frequency is much higher than the information frequency (like it is here), both FM and PM will look identical on a scope. FM and PM signals have a constant power. We need to use a spectrum analyzer to measure an FM or PM signal accurately.
Example 3-1

What is the frequency of the information signals in Figure 3-1? The horizontal timebase is set for 100 µS / division.

Solution:
The scope is measuring in the time domain, so we must first calculate the time period of the waveform:

\[ T = (10 \text{ Divisions})(100 \, \mu\text{s} / \text{Division}) = 1 \, \text{ms} \]

and the frequency is therefore:

\[ F = \frac{1}{T} = \frac{1}{1 \, \text{ms}} = 1 \, \text{kHz} \]

Example 3-2

Why do the modulated waveforms of Figure 3-1 appear as solid areas? Why can't we see the individual sine wave cycles of the AM and FM carriers?

Solution:
The frequency of the RF carriers is much higher than that of the information. In fact, the carrier frequency of both the AM and FM waveforms is 1 MHz. Recall that the information frequency is 1 kHz. Since 1 MHz is the same as 1000 kHz, 1000 cycles of carrier take place for every cycle of information. Since the oscilloscope is adjusted to show one cycle of information, it also sees 1000 cycles of carrier. The carrier sine waves blend together, forming a solid figure.

Tip:
When observing modulated signals on a scope, it usually best to use two scope channels. One of the scope channels is connected to the information, and the other is connected to the modulated output. The trigger must be set to the channel providing the information, in order to obtain a stable display. Many people forget this and have trouble getting accurate scope readings of transmitter outputs!

Figure 3-2 shows the conceptual process of amplitude modulation. Almost all AM transmitters work this way. When analyzing an actual circuit, it helps to keep this picture in mind.
The first stage in any transmitter is an oscillator. In a radio transmitter, it is usually called the RF carrier oscillator. The carrier oscillator converts the DC power supply energy into a radio frequency (RF) carrier wave. Oscillators will be studied in detail later.

The RF carrier wave contains no information until it is modulated. In order to amplitude modulate the carrier, its voltage (or power) must be changed. In order for the amplitude to be changed, the voltage or power gain of a subsequent stage must be changed.

The AM generator above has a special amplifier with a variable voltage gain called a modulator. This is really strange! The amplifiers you studied in fundamentals had a constant voltage or power gain, and only one input (this one has two!) An amplifier with a constant gain is called a linear amplifier.

What controls the gain of this amplifier? That's right -- there's a second input signal, the information signal. When the information signal goes positive, the amplifier's gain increases. This causes the output voltage (the AM signal) to swell or grow in amplitude. The opposite happens on the negative half-cycle of the information. The AM signal shrinks in amplitude because the amplifier's gain has decreased. Thus, amplitude modulation is created.

The variable-gain amplifier is a nonlinear amplifier because it has a gain that is not constant. One way of thinking of this amplifier is as a variable-resistor that controls the amount of carrier signal that gets through. The value of the "resistor" is controlled by the instantaneous value of the information signal.

A nonlinear amplifier distorts or changes the input signal. This is normally a bad thing! However, RF engineers carefully control this nonlinearity when they design modulators so that only a proper AM signal is produced.

A linear amplifier has a constant gain, and generates no distortion of the input signal. The graph of input-versus-output for a linear amplifier is a straight line (hence, the word "linear.") A nonlinear amplifier has a variable gain; its input-output graph is a curve. A nonlinear amplifier is always required to generate AM.
Section Checkpoint

3-1 List three applications of AM.
3-2 Why are FM and PM hard to observe on an oscilloscope?
3-3 What instrument is preferred for measuring FM and PM signals?
3-4 Why does the variable-gain amplifier stage in Figure 3-2 generate AM?
3-4 A non-________ amplifier stage is required to generate AM. (Fill in the blank)

3-2 Measuring AM Signals in the Time Domain

By interpreting the display of an AM signal on an oscilloscope, a technician can
determine a lot about the operation of an AM transmitter. By examining the waveform, a
technician can determine what type of information is modulating the transmitter, as well
as the percentage of modulation.

In an AM signal, the information is carried on top of the RF carrier. The actual shape
of the carrier is altered by the addition of the information during the process of modulation.
When we look at a modulated AM carrier wave, we tend to see an overall shape. The
imaginary lines that make up this shape are called the envelope.
Can you tell what is significant about the envelope? Take a look at Figure 3-3.

Yes -- the envelope is copy or duplicate of the intelligence signal! No matter what the
information is, the envelope will always imitate it. Take a look at Figure 3-4.
Figure 3-4: A triangular information signal

Again, the envelope looks just like the information signal on top. Another case might look like Figure 3-5.

Figure 3-5: A square wave information signal

As you can see from Figures 3-4 and 3-5, the envelope always matches the shape of the information. Figure 3-5 is a special case; can you tell what the source of the information might be? If you're thinking digital, you're on the right track. The information signal of Figure 3-5 is digital data, which is sent as a sequence of binary ones (highs) and zeros (lows). We'll study digital data communications in a later chapter.
In an AM signal, the percentage of modulation is a measure how strongly the carrier wave is being changed by the information. For radio, the higher the percentage of modulation, the louder the signal will be in the receiver's loudspeaker. Because percentage of modulation relates to sound volume, it would make sense that a broadcaster would try to attain as high a percentage of modulation as practical.

The maximum percentage of modulation is 100%, which represents maximum intelligence voltage (or volume). 0% modulation means that no modulation is taking place; the transmitter is said to be dead-keyed or unmodulated in this case.

The AM modulation index is the same information as the percentage of modulation. It is given the symbol \( m \) and can have a value between 0 (0% modulation) and 1 (100% modulation). When we calculate percentage of modulation in an AM signal, we are really calculating the modulation index.

Remember that the maximum modulation index is 1 (which corresponds to 100% modulation). A signal that is over 100 percent modulated is said to be overmodulated, which is an illegal condition. Overmodulation distorts the information and causes excessive bandwidth to be used by the transmitter.

**Example 3-3**

What percentage of modulation corresponds to a modulation index \( m \) of 0.5?

**Solution:**

Since \( m=0 \) means 0% modulation and \( m=1 \) means 100% modulation, we get:

\[
\%\text{Modulation} = m \times 100\% = 0.5 \times 100\% = 50\% \quad 1
\]

Remember that modulation index and percentage modulation are the same thing for an AM signal. (They are different quantities for FM, as we'll see later.)

AM modulation index can be defined by the formula:

\[
(3-1) \quad m = \frac{V_m}{V_c}
\]

Where \( V_m \) is the information voltage, and \( V_c \) is the carrier voltage.

Equation 3-1 defines the modulation index, but is not very helpful in making oscilloscope measurements. On a scope, it is difficult to separate the voltages \( V_m \) and \( V_c \) (but on a spectrum analyzer, it is quite easy, as we'll see).

To measure the modulation index on an oscilloscope, the following formula is used:

\[
(3-2) \quad m = \frac{V_{\text{max}} - V_{\text{min}}}{V_{\text{max}} + V_{\text{min}}}
\]

---

1 Note that multiplying any value by "100%" is really multiplying it by 1. We do this because a percentage is more intuitive for most people than a fraction.
Where $V_{max}$ is the maximum waveform voltage (the peak), and $V_{min}$ is the minimum waveform voltage (the trough) (See Figure 3-6).

![Figure 3-6: Measuring percentage modulation](image)

**Example 3-4**

What is the modulation index and percentage of modulation in Figure 3-6? The vertical sensitivity is 1 volt/division.

**Solution:**

Since we're measuring from an oscilloscope, we use equation 3-2:

$$m = \frac{V_{max} - V_{min}}{V_{max} + V_{min}} = \frac{3V_{pp} - 1V_{pp}}{3V_{pp} + 1V_{pp}} = 0.5$$

The percentage modulation is the modulation index expressed as a percentage:

$$\%Mod = 100\% \times m = 100\% \times 0.5 = 50\%$$

*Tip: To adjust an AM transmitter for 50% modulation, adjust the intelligence voltage so that the ratio of $V_{max}$ to $V_{min}$ is 3:1. (Notice how we have $V_{max}$=3 Volts and $V_{min}$=1 Volt in this case). Also, $V_{max}$ and $V_{min}$ can be measured in either peak or peak-to-peak units -- as long as they are both measured the same way.*
Example 3-5

What is the percentage of modulation in Figure 3-7? What is the condition of the transmitter? The vertical sensitivity is 1 volt/division.

Solution:
Since we're measuring from an oscilloscope, we again use Equation 3-2:

\[
m = \frac{V_{\text{max}} - V_{\text{min}}}{V_{\text{max}} + V_{\text{min}}} = \frac{2.8V_{\text{pp}} - 2.8V_{\text{pp}}}{2.8V_{\text{pp}} + 2.8V_{\text{pp}}} = 0 = \text{0\% Modulation}
\]

This is an example of an unmodulated transmitter. No information is being conveyed. We can also say that the transmitter is "dead keyed" or is transmitting "dead air." This is normally undesirable, especially in commercial broadcasting where time is money!
Example 3-6

Without doing any calculations, what is the percentage of modulation in Figure 3-8?

Solution:

Look at the trough in Figure 3-8. It’s nearly zero. *This indicates that 100% modulation (or something very close) is being achieved*. No calculations are needed!
Example 3-7

What is wrong with the AM signal of Figure 3-9?

Solution:
This is an example of overmodulation. The intelligence voltage is too big to fit onto the carrier, and as you can see, it has caused the trough to flatten. There are two problems here. First, the envelope is no longer an accurate copy of the information. The transmitted information will sound distorted.

Second, excessive bandwidth will be used, which can cause interference with adjacent stations on the band. This effect is called splatter. It is hard to see it on a scope (but again, a spectrum analyzer gives a much clearer view of what is happening).

Overmodulation is not a good practice. It distorts the information, uses up precious bandwidth, and can be stressful on station equipment. It could have been avoided here by reducing the voltage (volume) of the information.

Section Checkpoint

3-5 What is the envelope of an AM signal? What is significant about the shape of the envelope?
3-6 If the information is a square-wave, what shape will the envelope of the resulting AM signal be?
3-7 To calculate the percentage of modulation of an AM signal from an oscilloscope screen, what two measurements are required?
3-8 What is the maximum allowed percentage of modulation for an AM signal?
3-9 Why do AM broadcast stations use as high a percentage of modulation as possible?
3-10 What are two consequences of overmodulation?

3-3 Frequency Domain AM Analysis

As you'll recall from Chapter 2, there are two ways of examining electronic signals. We can look at signals in either the time or frequency domains. AM signals are very predictable in the frequency domain, which is important. When we know the frequency domain picture, it's easy to calculate and measure the bandwidth and total power of an AM signal.

Figure 3-10 shows a 100 kHz sine wave carrier in the frequency domain. How do we know this is a sine wave? Right, there's only one frequency present, 100 kHz. The sine wave is the only "pure" waveform, and it contains only one frequency. This particular sine wave is 10 volts RMS (about 14.1 volts peak).
What happens when this carrier signal is amplitude modulated? In the time domain, we know that the instantaneous voltage of the carrier will be forced to grow and shrink in step with the information. The nonlinearity of the modulator (the variable-gain stage) causes this to happen. In the frequency domain, the rapidly changing amplitude shows up as new frequencies called **sidebands**.

**Sidebands are new frequencies generated during the process of modulation.** They are created by the nonlinear distortion introduced by the modulator amplifier. All modulation creates sidebands - whether it be AM, FM, or PM.

Suppose that the 100 kHz carrier of Figure 3-10 is amplitude modulated by a 10 volt, 5 kHz information signal. The resulting frequency domain picture will look like Figure 3-11.
Note that some people use the term side frequency and others use sideband to describe these new frequencies. A side frequency is an individual frequency that can be part of a range of frequencies in a sideband. Since each of our sidebands in this example have only one frequency each (95 kHz for the lower sideband and 105 kHz for the upper sideband), we can use either term to correctly describe the signal.

The result of Figure 3-11 leads to some important questions. For example, what has happened to the 5 kHz information signal? To get the AM modulated signal of Figure 3-11, two signals had to be applied to the modulator stage. These were the 100 kHz sine wave carrier, and the 5 kHz information. The 5 kHz information signal seems to have disappeared! In reality, the information frequency (5 kHz) has been transformed into sideband frequencies (95 kHz and 105 kHz).

This transformation takes place with the help of the nonlinear transfer characteristic of the modulator stage. Therefore:

The sidebands contain the information. They can be thought of as an "encoded" representation of the intelligence.

To calculate the frequencies of the sidebands, we use the following equations:

\[
(3-3) \quad f_{usb} = f_c + f_m \\
(3-4) \quad f_{lsb} = f_c - f_m
\]

In these equations, \( f_c \) is the carrier frequency, and \( f_m \) is the information frequency.
The sidebands are the information expressed in a new way. Notice that we got two sidebands from one information frequency. Our original information voltage was 10 volts; yet the sidebands are only 5 volts each in Figure 3-11. Why is this so? Right -- because the information voltage causes two sidebands to form, its voltage must be divided by two in order to form each sideband. Therefore, we get:

\[(3-5) V_{usb} = V_{lsb} = \frac{V_m}{2}\]

Here, \(V_{usb}\) and \(V_{lsb}\) are the sideband voltages, and \(V_m\) is the information voltage.

Example 3-8

Calculate the bandwidth and modulation index of the AM signal shown in Figure 3-11. 

Solution:
We know that bandwidth is calculated by finding the difference between the highest and lowest frequencies in a signal. Therefore, we get:

\[BW = f_{\text{max}} - f_{\text{min}} = f_{usb} - f_{lsb} = 105kHz - 95kHz = 10kHz\]

Finding the modulation index is a little trickier, but not too difficult. Since we're working in the frequency domain, we will use equation 3-1:

\[m = \frac{V_m}{V_c}\]

We know that \(V_m\) and \(V_c\) are given in the original problem definition, however, we are asked to get the information from Figure 3-11. Finding \(V_c\) is easy; we just read it off the spectrum analyzer display as 10 volts.

Remember that each sideband comes from the information. Therefore, each sideband voltage is one-half of the information voltage. By using equation 3-5:

\[V_{usb} = V_{lsb} = \frac{V_m}{2}\]

\[V_m = V_{usb} + V_{lsb} = 2V_{usb/lsb}\]

Where \(V_{usb/lsb}\) is the voltage of either sideband (since they're identical).

\[V_m = 2V_{usb/lsb} = 2(5V) = 10 volts\]

Since we now know both \(V_m\) and \(V_c\), we can calculate the modulation index:

\[m = \frac{V_m}{V_c} = \frac{10V}{10V} = 1\]

The signal is 100% modulated.
TIP: You’ll often see a basic equation such as 3-1 or 3-2 used in many different ways. Don’t try to memorize all of these variations! Instead, just learn the basic equation, and concentrate on studying how we have applied it. Look for basic principles. For example, the basic idea here is that the information voltage "splits" into two sidebands during modulation. This will always happen in amplitude modulation.

Example 3-9

For the AM signal pictured in Figure 3-12, calculate the following:

a) The information frequency, $f_m$

b) The voltage in the upper sideband, $V_{usb}$

c) The bandwidth

d) $m$ and Percent Modulation

Solution:
The information frequency is carried in the difference between either sideband and the carrier. The lower sideband frequency $f_{lsb}$ is missing; however, we do know $f_{usb}$. By manipulating equation 3-3, we get:

$$f_m = f_{usb} - f_c = 813 \text{ kHz} - 810 \text{ kHz} = 3 \text{ kHz}$$

The sidebands are identical twins; their voltages are always equal. Therefore:

$$V_{usb} = V_{lsb} = 5 \text{ volts}$$ (The 5 volt value is given in Figure 3-12).

As we’ve done before, bandwidth can be calculated by:

$$BW = f_{\text{max}} - f_{\text{min}} = f_{usb} - f_{lsb}$$
However, \( f_{lsb} \) is missing! We do know \( f_m \) though, so we can readily complete this puzzle:

\[
f_m = 3 \text{ kHz from step (a)},
\]

Equation 3-4 tells us that:

\[
f_{lsb} = f_c - f_m
\]

Therefore:

\[
f_{lsb} = f_c - f_m = 810 \text{ kHz} - 3 \text{ kHz} = 807 \text{ kHz}
\]

\[
BW = f_{max} - f_{min} = f_{usb} - f_{lsb} = 813 \text{ kHz} - 807 \text{ kHz} = 6 \text{ kHz}
\]

**TIP:** There are better methods for calculating bandwidth. You may already have one in mind. A shortcut will be introduced momentarily.

Since we’re working in the frequency domain, Equation 3-1 should be used:

\[
m = \frac{V_m}{V_c}
\]

From Figure 3-12, we can see that \( V_c = 20 \text{V} \), and \( V_{lsb} = 5 \text{V} \). As before, we can get \( V_m \):

\[
V_m = 2 \ast V_{usb/lsb} = 2(5V) = 10 \text{ volts}
\]

Now that we know \( V_m \), we can substitute it into the definition for modulation index:

\[
m = \frac{V_m}{V_c} = \frac{10V}{20V} = 0.5 \text{ (The signal is 50% modulated.)}
\]

**A Shortcut for Bandwidth Calculation**

You may have already noticed that much of the work of part "c" above is unnecessary! There's a much simpler way of calculating bandwidth. If we look at the relative locations of the parts of the AM signal, this "shortcut" becomes clear.
In Figure 3-13, bandwidth is the total frequency "distance" between the maximum \( f_{\text{usb}} \) and minimum \( f_{\text{lsb}} \) frequencies in the signal. This distance is always twice the information frequency:

\[
BW = 2f_m
\]

**Example 3-10**

A certain AM signal has the following characteristics:
\( V_c = 100 \text{ V}, f_c = 2182 \text{ kHz} \); \( V_m = 25 \text{ V}, f_m = 2.5 \text{ kHz} \).

a) What bandwidth is required by the signal?

b) What is the modulation index \( m \) and the percentage of modulation?

c) Draw a spectrogram of the signal, showing all voltages.

**Solution:**

Using Equation 3-6: \( BW = 2f_m = 2(2.5kHz) = 5 kHz \)

Using Equation 3-1: \( m = \frac{V_m}{V_c} = \frac{25V}{100V} = 0.25 \) (The same as 25% modulation.)

To draw the spectrogram, we must find the sideband frequencies and voltages:

Using Equation 3-5: \( V_{\text{usb}} = V_{\text{lsb}} = \frac{V_m}{2} = \frac{25V}{2} = 12.5V \)