CHAPTER 10

CARRIER SYSTEMS

Introduction

The output from a transducer is normally in the form of an analog voltage related to the value of the measured variable. This voltage signal is usually transmitted directly by wire to the remaining elements of the instrumentation system for amplification, filtering, display, etc. In some cases, however, it is desirable to transmit the signal by means of a carrier system. This involves the use of a high frequency voltage source (the carrier) which is modulated by the lower frequency transducer signal. The modulation may be in the form of amplitude (AM), frequency (FM) or phase (PM) modification. Only AM systems will be considered here.

A radio transmitter together with a remote receiver is a familiar example of a carrier system. Here the signal (microphone output in the case of a radio station) is used to modulate the amplitude of a high frequency carrier signal. This electrical signal is converted to an acoustical signal, and transmitted. These signals are outside the frequency range of human hearing (40-16,000 Hertz) and are typically in the frequency range: 0.5 and 1.6 MegaHertz for an AM radio station. At the receiver the signal is band-pass filtered, demodulated and fed to a speaker to recover the original acoustic (speech or music) input.

An obvious advantage of using a carrier system here is that information can be transmitted over relatively large distances without using wires. Long cables can be a problem because they basically behave like low-pass filters and can attenuate the signal significantly; they also may enhance coupling with local power circuits causing harmonics of 60 Hertz to appear in the measured signal (see chapter on noise). So when we need to make a remote measurement, and the amplifiers and signal conditioning components of the measurement circuit have to be physically well separated from the transducer, we can use these transmitter-receiver systems to pass the signal from the transducer to the rest of the measurement/recording circuit.

It should be noted that low frequency acoustic waves attenuate a lot more slowly than high frequency waves and hence can be transmitted over longer distances. An example of this is whales communicating over long distances in the oceans. Before the advent of mechanized shipping, which creates low frequency noise, whales could communicate between oceans using low frequency acoustic signals. There are many low frequency noise sources in the environment. If low frequency signals are transmitted, both the signal and the extraneous noise will be picked up at the receiver. Since both occupy the same frequency range, they cannot be separated by filtering. The role of the modulation here is to move the signal to a frequency region where the background noise is very low. The distances over which the transmission is still possible is inversely related to frequency, and a function of the strength of the transmitted signal.

Another reason for modulating, apart from noise, is that the lower the frequency, the larger the device necessary to produce the transmitted wave. Very high frequencies can be
transmitted with very small transmitters. In measurement applications where transducers need to be small this is of importance. Strain gage configurations for measuring the twisting of rotating shafts sometimes use transmitter/receiver set-ups. Obviously direct wire connection of the gages to the rest of the measurement system is impractical when shafts are rotating.

Elements of a Carrier System

The basic elements of a carrier system are shown below.

\[ x(t) \rightarrow \text{Modulation Device} \rightarrow e_m(t) \rightarrow \text{Demodulator} \rightarrow x'(t) \]

- **Signal**: Input signal to be modulated.
- **Carrier**: High frequency signal used for modulation.
- **Modulated Signal**: Signal with carrier frequency added.
- **Recovered Signal**: Final output signal.

Fig. 1: Basic elements of a carrier system

A very simple device for modulating a carrier is a potentiometer.

\[ v(t) = \text{carrier} \]
\[ x(t) = \text{signal (relative output resistance as determined by the position of slide wire), } 0 \leq x(t) \leq R \]
\[ e_m(t) = \text{modulated signal} \]

Fig. 2: Potentiometer Circuit

In this circuit

\[ e_m(t) = \frac{x(t)}{R} \cdot v(t) \]  \hspace{1cm} (1)

Thus the output is proportional to the product of the signal and the carrier. This is characteristic of amplitude modulated (AM) systems. Often, the signal we wish to measure amplitude modulates a high frequency carrier signal \( v(t) \). The relatively low frequency of the signal we wish to measure is moved to a frequency region around the high frequency of the carrier. This is illustrated below.

Amplitude Modulation with a Sinusoidal Carrier

We will assume that \( x(t) \) varies harmonically about some mean value \( r_0 \) such that

\[ x(t) = r_0 + r_s \cos \omega_s t \]  \hspace{1cm} (2)
Also we assume that the carrier is given by:

\[ v(t) = V_c \sin \omega_c t \]  

Substitution of (2) and (3) into (1) yields:

\[
e_m(t) = \frac{V_c}{R} \sin \omega_c t [r_o + r_s \cos \omega_s t] = \frac{V_c r_o}{R} \sin \omega_c t + \frac{V_c r_s}{R} \sin \omega_c t \cos \omega_s t
\]

\[
e_m(t) = \frac{V_c r_o}{R} \sin \omega_c t + \frac{V_c r_s}{2R} \left[ \sin(\omega_c + \omega_s) t + \sin(\omega_c - \omega_s) t \right]
\]

Term 1 = Component at carrier frequency with amplitude proportional to D.C. component \(r_o\) of signal.

Term 2 = Component at \(\omega_c + \omega_s\) (upper side band frequency) with amplitude proportional to A.C. component of signal.

Term 3 = Component at \(\omega_c - \omega_s\) (lower side band frequency) with same amplitude as term 2.

The spectrum of the input signal and the corresponding modulated output for \(V_c/R = 1\) is shown in Fig. 3. Note that all of the information about the signal is contained in terms 1-3 of equation (4) and this is now centered around the high carrier frequency \(\omega_c\).
Some important conclusions can be drawn from a further examination of the spectrum. First we generalize the problem by observing that if the input signal contained a band of frequencies the spectrum might appear as shown in Fig. 4. Again the spectrum of the modulated signal contains sidebands which are related to the spectral content of the low frequency input signal. If the original signal contains frequencies up to \( B \) rad/s, then we will wish \( \omega_c \gg B \), so that when we modulate, the frequency content modulated signal is well above \( B \) rad/s. The frequency content of the modulated signal is in the region \( (\omega_c \pm B) \) rad/s. Often we choose \( \omega_c \geq 10 \omega_{\text{highest}} \), where \( \omega_{\text{highest}} \) is the highest frequency component in the signal before modulation. (In applications where low frequency noise is a problem, or where several signals are to be transmitted simultaneously, we may wish to choose \( \omega_c \) much higher than this.)

![Fig. 4: Illustration of Frequency Shifting due to Amplitude Modulation.](image)

An important feature of carrier systems is the fact that more than one signal may be transmitted simultaneously. One way in which this may be done is illustrated in Fig. 5. Each signal is multiplied by a different frequency carrier signal. The carrier frequencies are well separated so that there is no overlap in spectral content of the signals after modulation. This approach is used in radio and TV transmission.

![Fig. 5: An Example of the Transmission of Two Signals Simultaneously](image)
Demodulation of Amplitude Modulated Signals

Once the modulated signal $e_m(t)$ has been received and suitably filtered we must recover the original signal $x(t)$. This is done with a demodulator. The demodulation process can be rather complex, but the general concepts are illustrated here.

Consider the following time domain plots of the signals of interest.

![Fig. 6: Original Signal, Carrier Signal and Amplitude Modulated Signal](image)

The signal we wish to extract is the envelope of the modulated signal. This is the dashed line in the third graph in Fig. 6. However, just having the modulated signal, it is not possible to determine if the upper or lower envelope represent the desired signal. To choose the correct one, we use phase sensitive demodulation. The following figures illustrate the concept.

![Fig. 7: Illustration of Phase Sensitive Demodulation](image)

Note that a positive $e_s$ will produce a modulated signal having the same phase as the carrier, while a negative $e_s$ yields a signal 180° out of phase with the carrier. Therefore comparison of the phase of $e_m(t)$ with that of the carrier $v(t)$ will provide the correct sign. As an intermediate step $e_m(t)$ is usually rectified to simplify the circuitry. The overall process is shown in Fig 8 together with a block diagram of the phase sensitive demodulator system.
Another form of demodulation is to multiply the modulated signal by a signal proportional to the carrier signal. The modulated signal will have spectral content close to $\omega_c$. When you multiply the modulated signal by $A \sin \omega_c t$, the $\omega_c$ information gets split into two frequency regions: (1) close to 0 and (2) close to $2\omega_c$. Now putting this through a low-pass filter with a cut-off frequency below $\omega_c$, results in retaining just the low frequency signal; this signal should be proportional to $e_s(t)$. 

Fig. 8: Diagram showing phase sensitive demodulation
Example

Suppose that a signal \( e_m(t) \) is the result of modulating a low frequency displacement measurement with a high frequency carrier signal.

\[
y(t) = 50 \sin(\omega_c t) \cdot x(t)
\]

\[
x(t) = 0.1 + 0.2 \cos(10t) \quad \text{and} \quad \omega_c = 2000 \text{ rad/s}.
\]

\( x(t) \) and \( y(t) \) are shown in the figure below. Note that the carrier frequency is so high here that you cannot distinguish, on the scale plotted, the individual oscillations, and the graphs in Fig. 9 look like they have been shaded in.

![Graph showing original and modulated waveforms](image)

**Fig. 9: Original and modulated waveforms**

Let's demodulate this signal in the two ways described in this section.

**Phase Sensitive Rectification**

Assume that we know that the carrier signal was \( v(t) = 50 \sin 2000t \), and we have the measurement of \( y(t) \). To do phase sensitive rectification we wish to replace \( y(t) \) with either \( +\text{abs}(y(t)) \) or \( -\text{abs}(y(t)) \). To decide which sign, we check to see if at time \( t \), \( y(t) \) and \( v(t) \) have the same sign, in which case we choose the + sign. If they are of opposite sign we choose the – sign. Within a MATLAB program this operation may look something like the following.

```matlab
npoints=1000;
for i=1:npoints;
    if v(i)*y(i)>=0
        ps(i)=abs(y(i));
    else
        ps(i)=-abs(y(i));
    end;
end;
```


The result of this is just as if we had multiplied $x(t)$ by $\text{abs}(v(t))$, a rectified version of $v(t)$. This is shown in the next figure. This phase sensitive rectified signal has frequency content close to $0$ rad/s, close to $2\times \omega_c = 4000$ rad/s, close to $4\times \omega_c, 6\times \omega_c$, etc. After low pass filtering, only the close to zero information is retained; this is proportional to $x(t)$. You can filter in MATLAB using butter and filter. The filter specifications are a function of the sample rate. If in this case our sample rate was 32000 rad/s, a filter that would work would be:

```
wsamp=32000;
w_c=2000;

% Normalize cut-off frequency according to MATLAB Specifications
fc=2*(w_c/wsamp);
[b,a]=butter(10,fc);
z=filter(b,a,ps);
```

This is a 10th order Butterworth filter, which has a cut-off frequency of 200 dB/decade = 60 dB/Octave. $z(t)$, the output of the filter, is plotted in Fig. 10 along with the phase sensitive rectified signal.

![Diagram](place_holder.png)

**Fig. 10:** Phase sensitive demodulation:
(a) rectified signal
(b) filtered rectified signal

*Demodulation by Multiplication with the Carrier Signal*

Here the signal before low pass filtering is:

$$c(t) = y(t) \cdot v(t) = 100 \sin^2 2000t (\cos 10t + 0.5)$$
$$= 25 + 50 \cos 10t - 25 \cos 4000t - 50 \cos 4000t \cos 10t$$
$$= 25 + 50 \cos 10t - 25 \cos 4000t - 25 \cos 4010t - 25 \cos 3990t$$
Low pass filtering in the same way as before will remove the 4010, 4000 and the 3990 rad/s components, leaving ( 50 cos 10t + 25 ) which is proportional to x(t). c(t) and c(t) after filtering are shown in Fig. 11.

![Figure 11: Demodulation by multiplying by the carrier signal.](image)

(a) rectified signal. (b) filtered rectified signal.

**Summary**

Carrier systems provide an attractive means of transmitting transducer output signals in many cases. Some of their advantages are

1. Low frequency signals can be transmitted which are often more stable and less affected by noise. For this reason, signals are often modulated before transmission, so that any low frequency noise can be removed before demodulation.

2. Multiple signals may be transmitted on the same channel (multiplexing).

3. Certain devices involving capacitive or inductive elements require a high frequency A.C. input (the carrier) for their operation. The Bentley proximity probe is one example.

4. In applications that require remote sensing, whereby parts of the measurement system have to be physically separated from one another, modulation is used to create a high frequency signal that can be transmitted by a small device to a receiver that is connected to the rest of the measurement system. This avoids the use of long leads and is particularly useful in applications where contacting measurements are being taken on rotating machinery.

We have only considered systems involving the amplitude modulation of a sinusoidal carrier here. Other carrier signals are commonly employed, one of the most important being a high frequency train of narrow pulses (similar to a square wave carrier). This is used for transmitting both analog and digital signals. Further discussion is beyond the scope of these notes. However, the material presented here should provide a good understanding of the general principles underlying all carrier systems.