between AM and FM, and it must be developed further. First the similarity will be stressed.

In phase modulation, the phase deviation is proportional to the amplitude of the modulating signal and therefore independent of its frequency. Also, since the phase-modulated vector sometimes leads and sometimes lags the reference carrier vector, its instantaneous angular velocity must be continually changing between the limits imposed by ϕ_m; thus some form of frequency change must be taking place. In frequency modulation, the frequency deviation is proportional to the amplitude of the modulating voltage. Also, if we take a reference vector, rotating with a constant angular velocity which corresponds to the carrier frequency, then the FM vector will have a phase lead or lag with respect to the reference, since its frequency oscillates between $f_c - \delta$ and $f_c + \delta$. Therefore FM must be a form of PM. With this close similarity of the two forms of angle modulation established, it now remains to explain the difference.

If we consider FM as a form of phase modulation, we must determine what causes the phase change in FM. The larger the frequency deviation, the larger the phase deviation, so that the latter depends at least to a certain extent on the amplitude of the modulation, just as in PM. The difference is shown by comparing the definition of PM, which states in part that the modulation index is proportional to the modulating voltage *only,* with that of the FM, which states that the modulation index *is also inversely proportional to the modulation frequency*. This means that under identical conditions *FM and PM are indistinguishable for a single modulating frequency*. When the modulating frequency is changed the PM modulation index will remain constant, whereas the FM modulation index will increase as modulation frequency is reduced, and vice versa. This is best illustrated with an example.

EXAMPLE 5-4 A 25-MHz carrier is modulated by a 400-Hz audio sine wave. If the carrier voltage is 4 V and the maximum deviation is 10 kHz, write the equation of this modulated wave for (*a*) FM and (*b*) PM. If the modulating frequency is now changed to 2 kHz, all else remaining constant, write a new equation for (*c*) FM and (*d*) PM.

SOLUTION

Calculating the frequencies in radians, we have

$$\omega_c = 2\pi \times 25 \times 10^6 = 1.57 \times 10^8 \text{ rad/s}$$
$$\omega_m = 2\pi \times 400 = 2513 \text{ rad/s}$$

The modulation index will be

$$m = m_f = m_p = \frac{\delta}{f_m} = \frac{10{,}000}{400} = 25$$

This yields the equations

(*a*) $v = 4 \sin (1.57 \times 10^8 t + 25 \sin 2513t)$ (FM)
(*b*) $v = 4 \sin (1.57 \times 10^8 t + 25 \sin 2513t)$ (PM)

Note that the two expressions are identical, as should have been anticipated. Now, when the modulating frequency is multiplied by 5, the equation will show a fivefold increase in the (angular) modulating frequency. While the modulation index in FM is reduced fivefold, for PM the modulation index remains constant. Hence

(c) $v = 4 \sin (1.57 \times 10^8 t + 5 \sin 12{,}565t)$ (FM)
(d) $v = 4 \sin (1.57 \times 10^8 t + 25 \sin 12{,}565t)$ (PM)

Note that the difference between FM and PM is not apparent at a single modulating frequency. It reveals itself in the *differing behavior of the two systems when the modulating frequency is varied.*

The practical effect of all these considerations is that if an FM transmission were received on a PM receiver, the bass frequencies would have considerably more deviation (*of phase*) than a PM transmitter would have given them. Since the output of a PM receiver would be proportional to phase deviation (or modulation index), the signal would appear unduly bass-boosted. Phase modulation received by an FM system would appear to be *lacking in bass*. This deficiency could be *corrected by bass boosting the modulating signal prior to phase modulation*. This is the practical difference between phase and frequency modulation.

Frequency and amplitude modulation Frequency and amplitude modulation are compared on a different basis from that for FM and PM. These are both practical systems, quite different from each other, and so the performance and characteristics of the two systems will be compared. To begin with, frequency modulation has the following advantages:

1. The amplitude of the frequency-modulated wave is constant. It is thus independent of the modulation depth, whereas in AM modulation depth governs the transmitted power. This means that, in FM transmitters, low-level modulation may be used but all the subsequent amplifiers can be class C and therefore more efficient. Since all these amplifiers will handle constant power, they need not be capable of managing up to four times the average power, as they must in AM. Finally, *all* the transmitted power in FM is useful, whereas in AM most of it is in the transmitted carrier, which contains no useful information.
2. FM receivers can be fitted with amplitude limiters to remove the amplitude variations caused by noise, as shown in Section 5-2.2; this makes FM reception a good deal more immune to noise than AM reception.
3. It is possible to reduce noise still further by increasing the deviation (see Section 5-2.1). This is a feature which AM does not have, since it is not possible to exceed 100 percent modulation without causing severe distortion.
4. Commercial FM broadcasts began in 1940, decades after their AM counterparts. They have a number of advantages due to better planning and other considerations. The following are the most important ones:
   a. Standard frequency allocations (allocated worldwide by the International Radio Consultative Committee (CCIR) of the I.T.U.) provide a guard band between commercial FM stations, so that there is less adjacent-channel interference than in AM;
   b. FM broadcasts operate in the upper VHF and UHF frequency ranges, at which there happens to be less noise than in the MF and HF ranges occupied by AM broadcasts;

c. At the FM broadcast frequencies, the *space wave* is used for propagation, so that the radius of operation is limited to slightly more than line of sight, as shown in Section 8-2.3. It is thus possible to operate several independent transmitters on the same frequency with considerably less interference than would be possible with AM.

The advantages are not all one-sided, or there would be no AM transmissions left. The following are some of the disadvantages of FM:

1. A much wider channel is required by FM, up to 10 times as large as that needed by AM. This is the most significant disadvantage of FM.
2. FM transmitting and receiving equipment tends to be more complex, particularly for modulation and demodulation.
3. Since reception is limited to line of sight, the area of reception for FM is much smaller than for AM. This may be an advantage for cochannel allocations, but it is a disadvantage for FM mobile communications over a wide area. Note that this is due not so much to the intrinsic properties of FM, but rather to the frequencies employed for its transmission.

5-2 NOISE AND FREQUENCY MODULATION

Frequency modulation is much more immune to noise than amplitude modulation and is significantly more immune than phase modulation. In order to establish the reason for this and to determine the extent of the improvement, it is necessary to examine the effect of noise on a carrier.

5-2.1 Effects of Noise on Carrier—Noise Triangle

A single-noise frequency will affect the output of a receiver only if it falls within its bandpass. The carrier and noise voltages will mix, and if the difference is audible, it will naturally interfere with the reception of wanted signals. If such a single-noise voltage is considered vectorially, it is seen that the noise vector is superimposed on the carrier, rotating about it with a relative angular velocity $\omega_n - \omega_c$. This is shown in Figure 5-5. The maximum deviation in amplitude from the average value will be V_n, whereas the maximum phase deviation will be $\phi = \sin^{-1}(V_n/V_c)$.

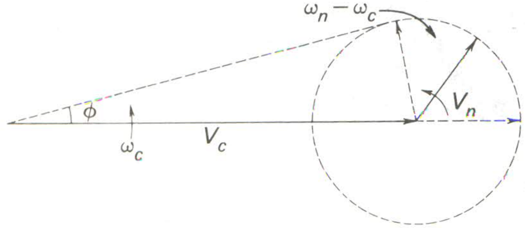

FIGURE 5-5 Vector effect of noise on carrier.