# Frequency modulation and sidebands

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**While most people are familiar with Amplitude Modulation and the relationship between carrier and sidebands, FM is something of a mystery. This article treats that subject.**

Frequency modulation is a widely accepted form of transmitting intelligence via radio waves. The inherently higher signal to noise ratios possible with FM (as compared to AM) have led to its complete dominance in the field of high-fidelity broadcasting. In the area of point-to-point VHF communications, the simplicity and lower power requirements of FM transmitters have helped to make this the mode enjoyed by a majority of users. Certainly, in the VHF amateur bands, FM is the most popular form of modulation.

Only the wider bandwidth required by an FM signal has prevented it from being a serious contender to AM in the congested high frequency band. But what is the bandwidth required by an FM transmitter? By the use of photographic displays from a spectrum analyser we aim to graphically illustrate the answer to this question.

In amplitude modulation the frequency spectrum of the transmitter output is relatively simple. A central carrier is surrounded on each side by a single lower-intensity sideband. The modulation percentage changes only the level of the sideband components, but does not alter the general form of the spectrum. However, the situation is radically different for a frequency modulated signal. The appropriate parameter in FM is not percentage modulation but modulation index (m). As this index changes in value not only the amplitude of the sidebands change, but new sidebands appear and the whole shape of the frequency spectrum alters.

The modulation index is defined as the ratio of the maximum carrier frequency change (or deviation) $f_d$ to the modulating audio frequency $f_m$ producing this change. That is: $m = f_d / f_m$

| Category | Frequency deviation | Modulation frequency | Modulation index | Signal Bandwidth |
|---|---|---|---|---|
| WBFM | 75kHz | 50Hz<br>15kHz | 1500<br>5 | 200kHz |
| NBFM | 5kHz | 500Hz<br>3000Hz | 10<br>1.5 | 15kHz |

**Table 1.** Typical parameters for wideband (WBFM) and narrowband (NBFM) frequency modulation.

In AM, it is usually desirable to achieve a percentage modulation of 100%. There is, however, no single most desirable value for the modulation index, and several factors in any communications system influence the choice of m. These include system bandwidth restrictions and noise reduction considerations. The first requirement is that the signal level must exceed the system noise level. If, and only if this is the case, then FM displays a noise-voltage reduction factor (R) over AM of:

$$R = \sqrt{3}m = 1.73m.$$

This is shown graphically in Fig. 1. Three assumptions are made in deriving this equation. They are that the FM receiver has complete signal limiting, that the IF passbands are matched to the signal in each case, and that the FM and AM receiver audio passbands are the same.

Examination of Fig. 1 shows that the break-even point occurs at m = 0.6. That is, the modulation index must exceed 0.6 if any noise reduction benefit is to accrue from the use of FM. Above this, the amount of noise reduction increases as the value of m increases. When m = 10, FM displays a noise-voltage reduction over AM of 25dB.

It might thus seem advantageous to use as high a value of m as possible. However, as always, we never get something for nothing, and two

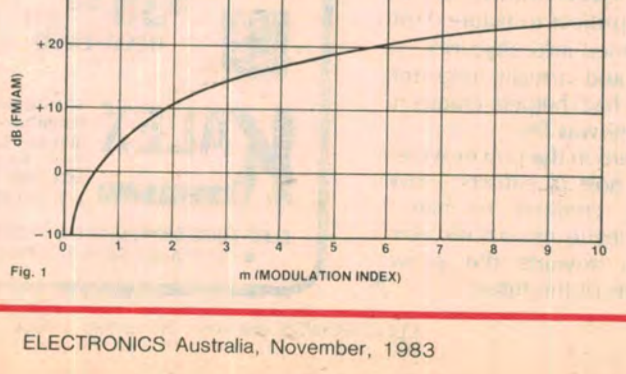


Fig. 1

| Modulation Index (m) | Bandwidth (BW) (in multiples of $f_m$) |
|---|---|
| 0.5 | 2 |
| 1 | 4 |
| 2 | 6 |
| 5 | 12 |
| 10 | 22 |

**Table 2.** Bandwidth versus modulation index. $f_m$ is the (constant) modulating frequency.

problems arise. The first problem, as we shall see shortly, is the increased bandwidth that follows the increase of m. If transmissions have a certain limited frequency allocation, the bandwidth of each must necessarily be restricted.

The second problem relates to the dispersion of the total transmitter energy into more and more sidebands as the frequency deviation is increased. Eventually a point is reached where the amplitude of the sidebands (at the receiver) is below the system noise and the curve of Fig. 1 is no longer appropriate. In this case, an AM signal buried in the noise is more "copyable" than an FM signal similarly enmeshed.

In practice, FM transmissions tend to fall into two categories, designated wideband and narrowband FM (see Table 1). The first category, wideband FM, is normally used in high-quality broadcast situations (88-108MHz band and TV sound) and has a modulation index that varies between about five and 2000 depending upon the audio modulating frequency. Narrowband FM is used in VHF and UHF point-to-point systems and has a modulation index that typically varies from one to 10 for the narrower range of audio frequencies used for such communications.

Fig. 2 shows a number of FM spectra where the modulation index varies from 0.5 to 10.0. This was achieved by changing only the frequency deviation of the carrier – all other parameters were kept constant. The centre frequency used was 435.0MHz and the modulating frequency was 10kHz. The spectrum analyser was set to display amplitudes on a linear scale and thus any sideband with an amplitude significantly below one-tenth of the unmodulated carrier will not appear. This is also a good criterion to use in the computation of bandwidth.

A quick inspection of these spectra reveals that as the frequency deviation, and thus the modulation index, is increased, the number of sidebands and the frequency range they occupy increases. The separation between adjacent sidebands, however, remains constant at 10kHz, the modulating frequency.

A closer inspection of the individual spectra reveals a number of other interesting details. When the modulation index is 0.5, the FM spectrum looks remarkably like that of an AM signal with about 50% modulation. It is significant that around this value of m there is also no difference in signal-to-noise ratio between equivalent AM and FM signals (providing of course that the FM signal is above the system noise). However, this similarity is not as great as it first appears, a fact attested to by the inability of a centrally tuned AM receiver to demodulate this signal.

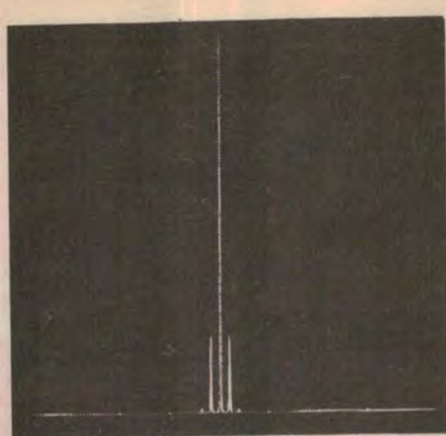

Fig.2(a): $f_d$ = 5kHz, m = 0.5

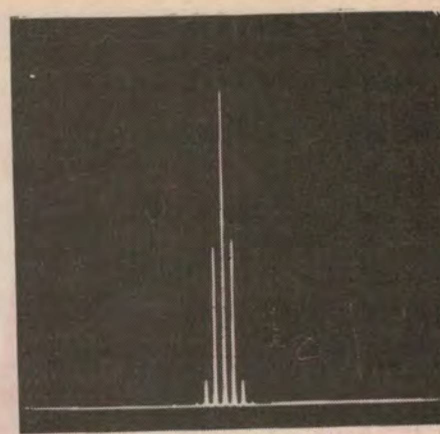

Fig.2(b): $f_d$ = 10kHz, m = 1.0

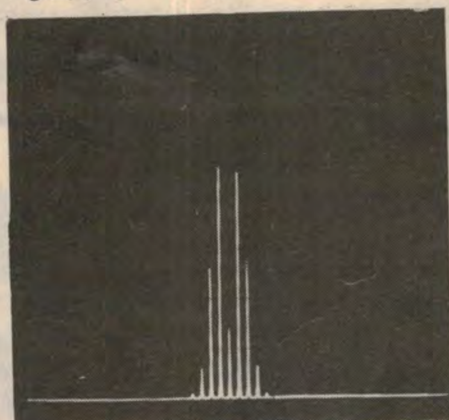

Fig.2(c): $f_d$ = 20kHz, m = 2.0

Fig.2(d): $f_d$ = 25kHz, m = 2.5

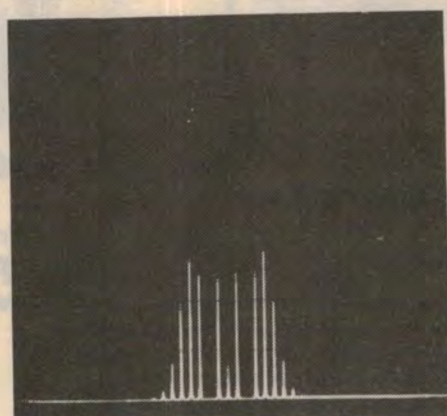

Fig.2(e): $f_d$ = 50kHz, m = 5.0

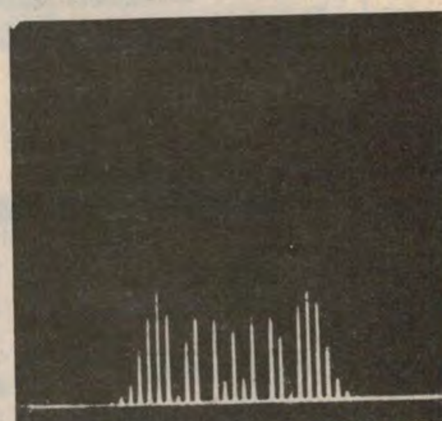

Fig.2(f): $f_d$ = 100kHz, m = 10.0

The discrepancy occurs because the spectrum analyser does not display all the information contained in the signal. While it does indicate the average power in each frequency component, it says nothing about their relative phase. If we had a phase indication we would see that the lower FM sideband was exactly 180° out of phase with its AM counterpart. (The moral of this is to try to get all the facts before jumping to any conclusion.)

As the modulation index is increased to 1.0, two things happen: a second pair of sidebands appear, displaced by twice the modulation frequency from the carrier, and the amplitude of the carrier is reduced. In an FM transmitter, the total power output is always constant, irrespective of what modulation is occurring. Thus, if more sidebands are produced, their energy can only come from the frequency components already present. In effect, frequency modulation removes energy from the carrier and puts it into the sidebands.

When the modulation index is increased to 2.0, three pairs of sidebands are present. The amplitude of the carrier is also dramatically diminished and the first sideband pair become the dominant frequency components. When m = 2.5 (or more exactly 2.4), the carrier component disappears entirely. This is not a permanent state of affairs as can be seen for the spectra where m equals 5 and 10.

As m increases above 2.4 the amplitude of the carrier begins to increase but it now has the opposite phase. Similar behaviour occurs with each of the sideband pairs. It can be seen that for m = 5, the second sideband pair is absent, and for m = 10 the third sideband pair is missing (the sixth sideband pair also has a very low amplitude). If we were to graph the amplitude of the carrier or any sideband pair as a function of m, we would find that they had the form of a damped sine wave (eg an oscillating mass on a spring with friction present).

If we count the number of sidebands present in each spectrum of Fig. 2 we can draw up a list similar to that of Table 2. From this we can develop an empirical equation giving the bandwidth (BW) required for each modulation index: This is:

$$BW = 2(m+1)f_m.$$

If we express m in terms of frequency deviation the relation becomes:

$$BW = 2(f_d+f_m).$$

That is, the bandwidth of an FM transmission is twice the sum of the frequency deviation and modulation frequency. This is quite a useful formula to remember.

Once we have decided on the frequency deviation to be used in a given situation, it is useful to examine how the frequency spectrum changes as the audio modulation frequency is varied over its specified range. The results are shown in Fig. 3. Here the modulation index varies from 2.5 to 100.0. Unlike Fig. 2, however, the frequency deviation has been kept constant at 50kHz. Only the modulation frequency has been varied. The centre frequency is still 435.0MHz.

These photographs show spectra with no qualitative differences from those of Fig. 2. It is difficult to count the individual sidebands for the higher values of m, but as m becomes large we might note that the envelope of the spectrum becomes U-shaped. There is a sharp boundary at the limits of the spectrum. In this situation, the modulation frequency is so much smaller than the frequency deviation that the bandwidth is effectively just twice the deviation.

Many texts will stress that frequency modulation produces an infinite number of sidebands. Although this may be theoretically true, in practice, as can be readily seen from the spectra shown here, the number of significant sidebands is quite limited, and the bandwidth occupied by these can be easily determined.

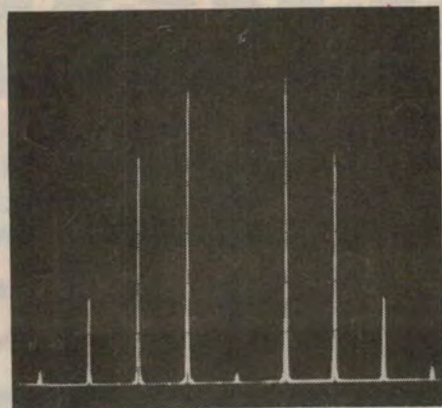

Fig.3(a): $f_m$ = 20kHz, m = 2.5

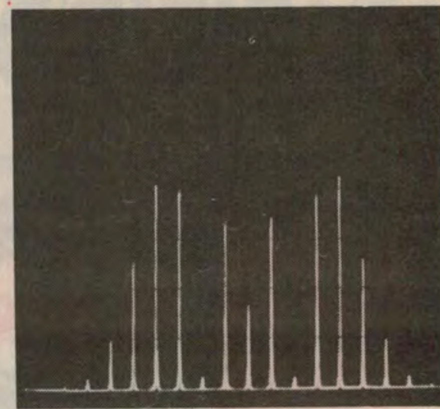

Fig.3(b): $f_m$ = 10kHz, m = 5.0

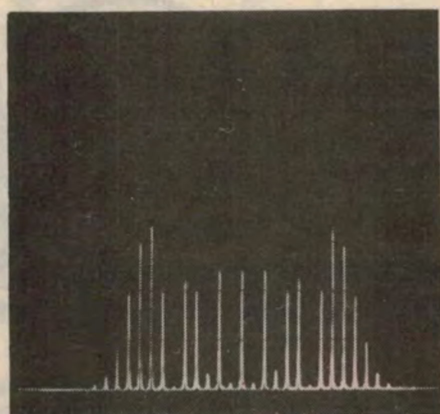

Fig.3(c): $f_m$ = 5kHz, m = 10.0

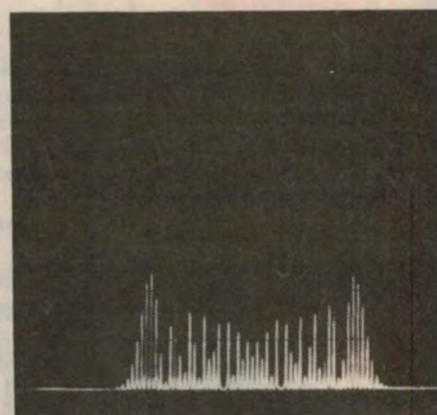

Fig.3(d): $f_m$ = 2kHz, m = 25.0

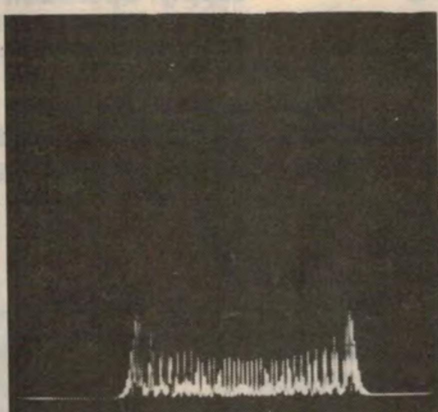

Fig.3(e): $t_m$ = 1kHz, m = 50.0

Fig.3(f): $f_m$ = 500Hz, m = 100.0