FINE TUNING FM FINAL STAGES

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WHY IS CORRECT TUNING IMPORTANT?

Tuning the output of a tube type power amplifier usually involves several different interacting adjustments. The resonant frequency of the output circuit is adjusted to minimize plate current by a control that is often called "OUTPUT TUNING", while the power output level is adjusted by a control called "OUTPUT LOADING". A third kind of adjustment called "SCREEN VOLTAGE" is related to the setting of the output loading in amplifiers that utilize a tetrode tube. Tuning the input of the power amplifier usually involves two kinds of adjustments. The resonant frequency of the grid circuit is set by the "INPUT TUNING" control while the input impedance match is set by the "INPUT MATCHING" control. Some of the newer transmitter designs have eliminated the need for the input matching control by incorporating broadband matching networks. Correct adjustment of these controls is essential not only to achieving peak efficiency, but also to making the passband of the amplifier as transparent as possible to the wideband FM signal that must pass through it. When automatic power control (APC) is used with tetrode amplifiers, the allowance for "headroom" in the tuning procedure is essential if screen overloads are to be avoided.

Achieving "peak efficiency", adequate "APC headroom", and a "centered passband" all simultaneously is generally not possible, so a reasonable compromise will be the objective when tuning the final stage.

FM MODULATION THEORY

FM SIDEBAND STRUCTURE

The frequency modulated RF output spectrum contains many sideband frequency components, theoretically an infinite number. They consist of pairs of sidebands spaced from the carrier frequency by multiples of the modulating frequency. When the modulation index is small (M=0.5) the amplitude of the second and higher order sidebands is small so that the output consists mainly of the carrier and the pair of first-order sidebands, as illustrated in Figure-1A. The total transmitter RF output power remains constant with modulation, but the distribution of that power into the sidebands varies with the modulation index so that power at the carrier frequency is reduced by the amount of power added to the sidebands.

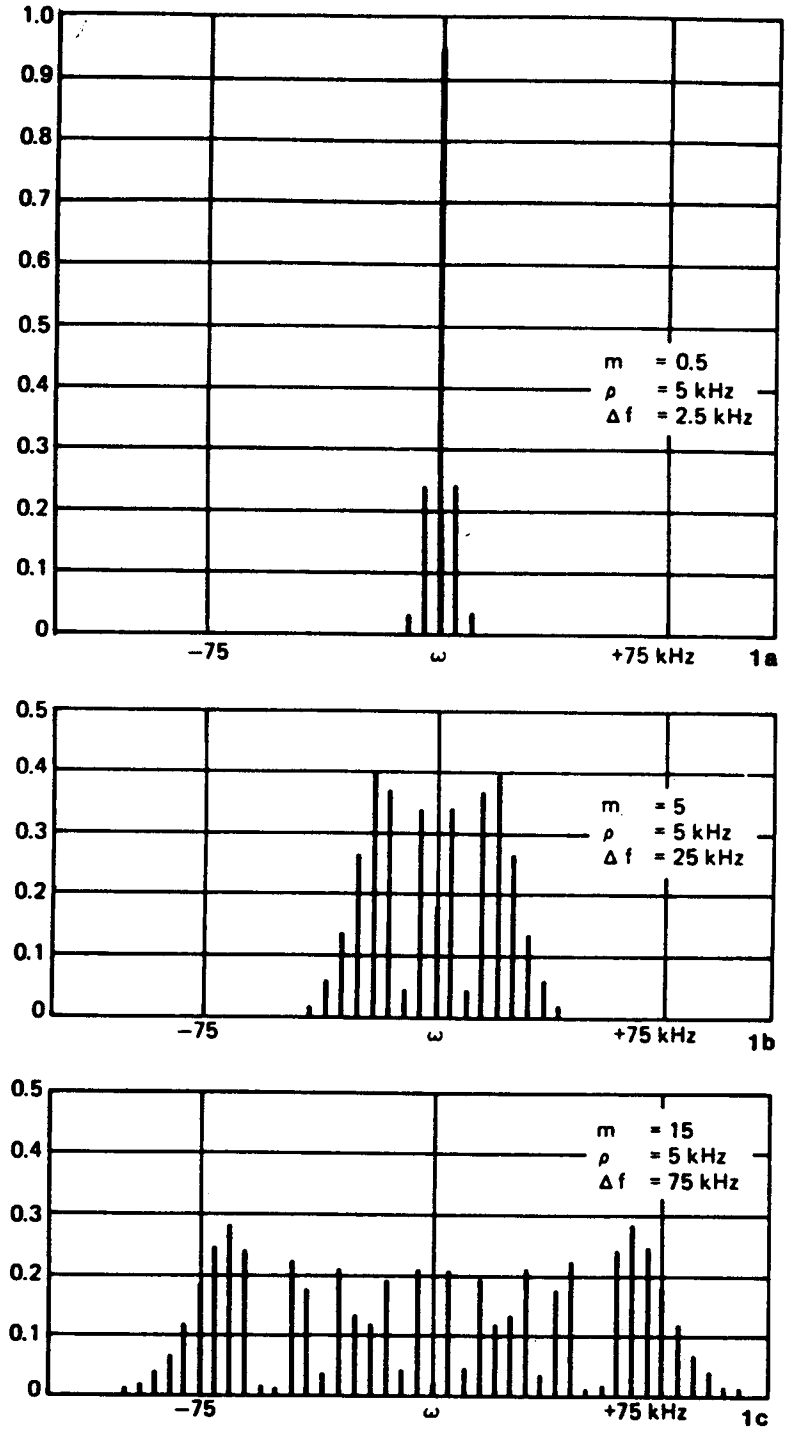

FIGURE 1. RF SPECTRUM WITH MODULATION INDICES OF 0.5, 5, AND 15

As the modulation index is increased as in wide deviation FM broadcasting, the higher order sidebands become more prominent. The amplitude and phase of the carrier (Jo) as well as the sidebands (J1 thru Jn) can be expressed mathematically by making the modulation index (M) the argument of a simplified Bessel function.

$E(t) =$	total RF output voltage
$A[J0\ (M)\sin Wc(t)]$	carrier amplitude
$+[J1\ (M)\sin(Wc+Wm)t]$	first order upper sideband
$-[J1\ (M)\sin(Wc-Wm)t]$	first order lower sideband
$+[J2\ (M)\sin(Wc+2Wm)t]$	second order upper sideband
$+[J2\ (M)\sin(Wc-2Wm)t]$	second order lower sideband
$+[J3\ (M)\sin(Wc+3Wm)t]$	third order upper sideband
$-[J3\ (M)\sin(Wc-3Wm)t]$	third order lower sideband
$\pm[Jn\ (M)\sin(Wc\pm nWm)t]$....	higher order sidebands

WHERE:

A = The unmodulated carrier amplitude constant
Jo = The modulated carrier amplitude
J1,J2,J3...Jn are the amplitudes of the nth order sidebands
M = The modulation index
Wc = 2 (π)(Fc) The carrier frequency
Wm = 2 (π)(Fm) The modulating frequency

The numeric values of the Bessel functions (Jo thru Jn) which express the amplitudes of the various frequency components can be found in mathematical tables. Figure-2 shows a graphical representation of how the Bessel function values for the carrier and the first eight pairs of sidebands vary with the modulation index.

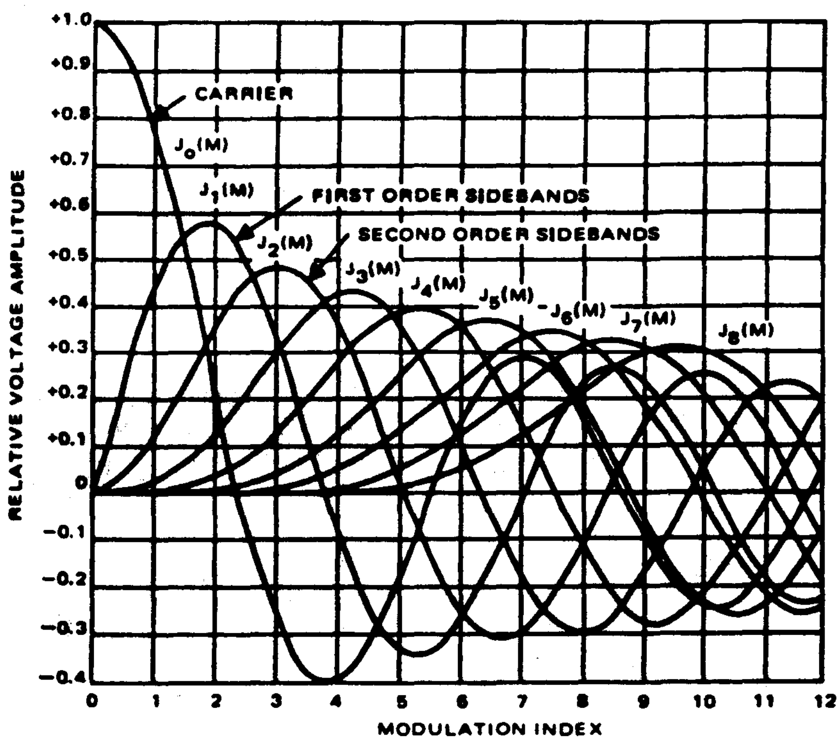

FIGURE-2. RELATIONSHIP OF CARRIER AND SIDEBAND AMPLITUDES TO MODULATION INDEX

Figures 1B and 1C illustrate the frequency components present for modulation indices of 5 and of 15. Note that the number of significant sideband components becomes very large with a high modulation index. The total bandwidth occupied extends beyond ±75 kHz from the carrier depending upon the modulating frequency. This single tone modulating frequency analysis is useful in understanding the general nature of FM and for making tests and measurements. When program modulation is applied, there are many more sideband components present and they are varying so much that sideband energy becomes distributed over the entire occupied bandwidth rather than appearing at discrete frequencies.

After examining the Bessel function and the resulting spectra, it becomes clear that the occupied bandwidth of an FM signal is far greater than the amount of deviation from the carrier that one might incorrectly assume as the bandwidth. In fact, the occupied bandwidth is infinite if all the sidebands are taken into account, so it is now clear that a frequency modulation system would require the transmission of an infinite number of sidebands for perfect demodulation of information. In practice, a signal of acceptable quality can be transmitted in the limited bandwidth assigned to an FM channel.

BANDWIDTH VERSUS DISTORTION

Consider the system shown in Figure-3A, where a perfect FM modulator is connected to a perfect demodulator via an RF path of wide bandwidth. The demodulated baseband shown in Figure-3C contains no distortion components.

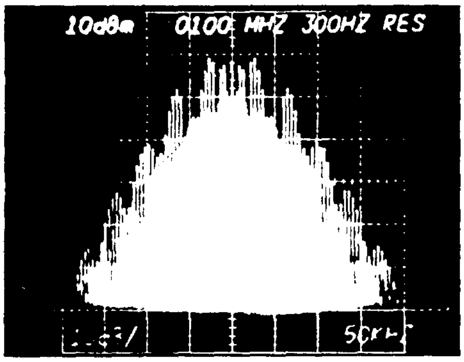

FIGURE 3A.
WIDEBAND RF SPECTRUM TO DEMODULATOR

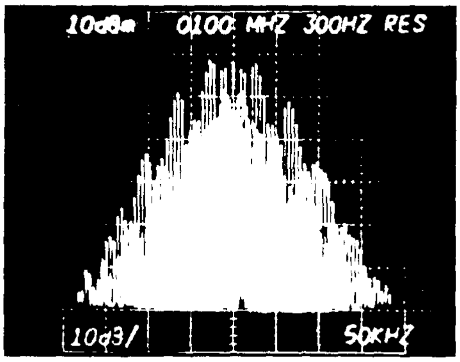

FIGURE 3B.
BANDWIDTH LIMITED RF SPECTRUM TO DEMODULATOR

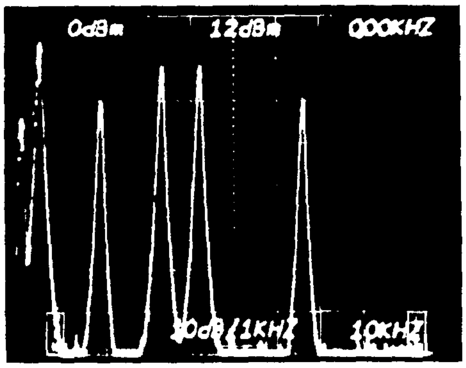

FIGURE 3C.
DEMODULATED BASEBAND SPECTRUM FOR WIDEBAND RF SPECTRUM

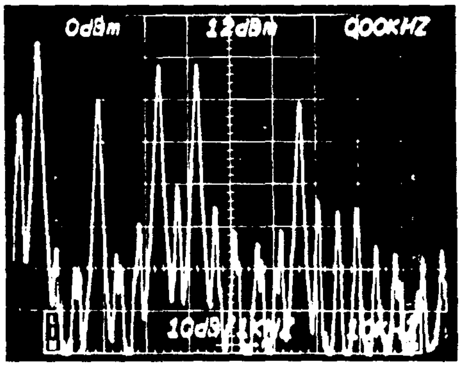

FIGURE 3D.
DEMODULATED BASEBAND SPECTRUM FOR BANDWIDTH LIMITED RF SPECTRUM SHOWING DISTORTION PRODUCTS

Figure-3B shows the effects of an RF bandpass filter on the RF spectrum of composite baseband consisting of stereophonic baseband modulated at 4.5 kHz only on one channel along with an unmodulated 67 kHz SCA subcarrier. The only distortion evident on the RF spectrogram is the attenuation of sidebands greater than 200 kHz from the center frequency and the amplitude differences between the lower and upper sideband pairs. Figure-3D shows the corresponding effects observed on the demodulated baseband spectrum for the same signal. Note the creation of many undesired intermodulation terms which will cause crosstalk into subcarrier bands. As you can clearly see, the distortion in this FM system does depend on the amount of bandwidth available versus the modulation index being transmitted.

HOW DOES TUNING AFFECT THE FM SIDEBANDS

The higher order FM sidebands will be slightly attenuated in amplitude and shifted in phase as they pass through the final amplifier stage. These alterations in the sideband structure that are introduced by the amplifier passband, result in distortion after FM demodulation at the receiver. The amount of distortion is dependent on the available bandwidth versus the modulation index being transmitted. For a given bandwidth limitation, the distortion can usually be minimized by centering the passband of the amplifier around the signal being transmitted. This will cause the amplitude and phase errors to affect both the upper and lower sidebands equally or symmetrically. Tuning an amplifier for maximum power output or for best efficiency does not necessarily result in a centered passband. One way to center the passband is to tune the amplifier for minimum synchronous AM modulation while applying FM modulation to the transmitter.

TWO TYPES OF AM MODULATION

The perfect FM transmitter would have a absolutely constant output, regardless of FM modulation or power supply variations. In practice, there is always some residual amplitude modulation of the FM transmitter output. There are two types of AM modulation that are of interest to the FM broadcast engineer:

1. Asynchronous AM modulation is measured without FM modulation and is primarily related to power supply ripple.

2. Synchronous AM modulation (incidental AM) measured with FM modulation is related to the tuning and overall bandwidth of the system.

ASYNCHRONOUS AM

Residual amplitude modulation of the transmitter output, due primarily to power supply ripple, is measured with an AM envelope detector. Most FM modulation monitors include an AM detector for this purpose. This detector should include 75 microsecond de-emphasis on its output. The residual AM noise in a properly operating FM transmitter will be at least 50dB below the level which would represent 100 percent amplitude modulation of the carrier. If the transmitter is unable to meet the 50dB requirement, the problem can usually be traced to a power supply component or to line imbalance in a three phase system.

SYNCHRONOUS AM

Synchronous AM is a measure of the amount of incidental amplitude modulation introduced onto the carrier by the presence of FM modulation. This measurement is very useful for determining the proper tuning of the transmitter. Since all transmitters have limited bandwidth, there will be a slight drop-off in power output as the carrier frequency is swept to either side of the center frequency. This slight change in RF output level follows the waveform of the signal being applied to the FM modulator causing AM modulation in synchronization with the FM modulation. The concept is similar to the slope detection of FM by an AM detector used in conjunction with a tuned circuit.

Both types of AM noise measurements are made directly at the transmitter output (or an accurate sample of its output). No amplifying or limiting equipment may be used between the transmitter output and the AM detector since nonlinearities in this equipment could modify the AM noise level present. Since the transmitter cannot be fully amplitude modulated, an equivalent reference level must be established indirectly by a measurement of the RF carrier voltage.

Refer to the instructions of the detector manufacturer to determine this reference level. Generally, the reference level is determined by setting a carrier level meter to a specified reading or to obtain a specific DC voltage level at the output of the detector diode without modulation.

WHY IS SYNCHRONOUS AM IMPORTANT?

Measurement of synchronous AM gives the station engineer an idea of the overall system bandwidth and whether the passband is positioned correctly. Tuning for minimum synchronous AM will assure that the transmitter passband is properly centered on the FM channel.

HOW GOOD SHOULD SYNCHRONOUS AM BE?

Synchronous AM of 40dB or more below equivalent 100% AM, is considered to be acceptable. Some of the newer single tube transmitters can be adjusted for 50dB or more suppression of synchronous AM. An approximation to the overall system bandwidth can be related to the synchronous AM as follows:

PEAK TO PEAK SYNCHRONOUS AM (below equivalent 100% AM) (with ±75 kHz @ 400 Hz FM)	APPROXIMATE BANDWIDTH (-3dB)
-40dB	1.1MHz
-45dB	1.4MHz
-50dB	2.0MHz
-55dB	2.5MHz
-60dB	3.4MHz

TUNING YOUR TRANSMITTER FOR PEAK PERFORMANCE

All optimization should be done with any automatic power control (APC) system disabled so that the APC will not chase the adjustment in an attempt to keep the output power constant. The transmitter should be connected to the normal antenna system rather than to a dummy load. This is because the resistance and reactance of the antenna will be different from the dummy load and the optimum tuning point of the transmitter will shift between the two different loads.

The tuning sequence is:

INITIAL TUNING AND LOADING

The transmitter is first tuned for normal output power and proper efficiency according to the manufacturer's instruction manual. The meter readings should closely agree with those listed on the manufacturer's final test data sheet if the transmitter is being operated at the same frequency and power level into an acceptable load.

INPUT TUNING AND MATCHING

The input tuning control should first be adjusted for maximum grid current and then fine tuned interactively with the input matching control for minimum reflected power to the driver stage. Note that the point of maximum grid current may not coincide with the minimum reflected power to a solid state driver. This is because a solid state driver may actually output more power at certain complex load impedances than into a 50 ohm resistive load. The main objective during input tuning is to obtain adequate grid current while providing a good match (minimum reflected power) to the coaxial transmission line from the driver. In the case of an older transmitter with a tube driver integrated into the grid circuit of the final amplifier, the driver plate tuning and the final grid tuning will be combined into one control which is adjusted for maximum grid current.

OUTPUT TUNING

The output tuning control adjusts the resonant frequency of the output circuit to match the carrier frequency. As resonance is reached, the plate current will drop while both the output power and screen current rise together. Under heavily loaded conditions this "dip" in plate current is not very pronounced, so tuning for a "peak" in screen current is often a more sensitive indicator of resonance.

Amplifiers utilizing a folded halfwave cavity will display little interaction between output tuning and output loading because the output coupling loop is located at the RF voltage null point on the resonant line. Quarter-wave cavities will require interactive adjustment of output tuning and output loading controls, since changes in loading will also affect the frequency of the resonant line.

OUTPUT LOADING

There is a delicate balance between screen voltage and output loading for amplifiers utilizing a tetrode tube. Generally there is one combination of screen voltage and output loading where peak efficiency occurs. At a given screen voltage increasing the amplifier loading will result in a decrease in screen current, while a decrease in loading will result in an increase in screen current. As the screen voltage is increased to get more output power, the loading must also be increased to prevent the screen current from reaching excessive levels. Further increases in screen voltage without increased loading will result in a screen overload without an increase in output power.

AUTOMATIC POWER CONTROL HEADROOM

Automatic power control (APC) feedback systems are utilized in many transmitters to regulate the power output around a predetermined setpoint with variations in AC line voltage or changes in other operating parameters. Most modern FM broadcast transmitters utilize a single high gain tetrode as the final amplifier stage with adjustment of the screen voltage providing fine adjustment of the output power. For each power output level there is one unique combination of screen voltage and output loading that will provide peak operating efficiency. If the screen voltage is raised above this point without a corresponding increase in loading, there will be no further increase in power output with rising screen voltage and screen current. If the screen voltage is raised without sufficient loading, a screen current overload will occur before the upward adjustment in power output is obtained.

To avoid this problem, it is a good idea to tune the transmitter with slightly heavier loading than necessary to achieve the desired power output level in order to allow for about 5% headroom in adjustment range. The output loading can be adjusted for a "peak" in output power of 5% over the desired level and the screen voltage can then be reduced enough to return to the desired level. This procedure will allow headroom for an APC system controlling screen voltage and will result in about a 1% compromise in efficiency, but it will assure the ability to increase power output up to 5% without encountering a screen overload.

MINIMIZING SYNCHRONOUS AM

After the correct loading point has been set, FM modulate 100% (±75 kHz) at 400Hz and fine-adjust the transmitter's input tuning and output tuning controls for minimum 400Hz AM modulation as detected by a wideband envelope detector (diode and line probe). The input matching and output loading controls should not need any further adjustment. It is helpful to display the demodulated output from the AM detector on an oscilloscope while making this adjustment. Note that as the minimum point of synchronous AM is reached, the demodulated output from the AM detector will double in frequency from 400Hz to 800Hz, because the fall-off in output power is symmetrical about the center frequency causing the amplitude variations to go through two complete cycles for every one FM sweep cycle. This effect is illustrated in Figure-4. It should be possible to minimize synchronous AM while maintaining output power and sacrificing little efficiency in a properly operating power amplifier.

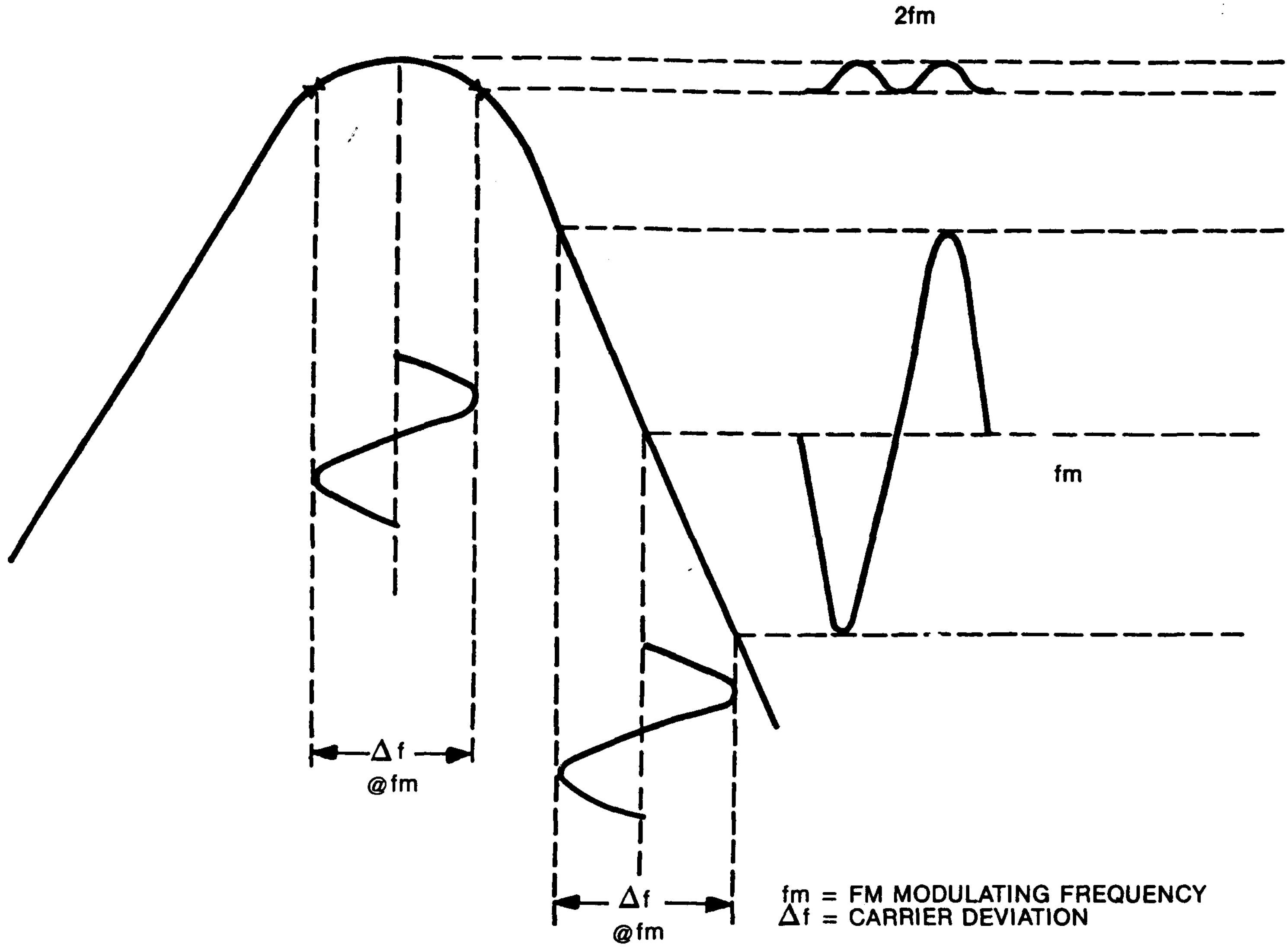

FIGURE 4. SYNCHRONOUS AM WAVEFORMS

THE NEED FOR A PRECISION ENVELOPE DETECTOR

Care must be taken when making these measurements that the test set-up does not introduce synchronous AM and give erroneous readings which would cause the operator to mistune the transmitter to compensate for errors in the measuring equipment.

The input impedance of the envelope detector must provide a nearly perfect match so that there is a very low VSWR on the sampling line. Any significant VSWR on the sampling line will produce synchronous AM at the detector because the position of the voltage peak caused by the standing wave moves along this line with FM modulation. Unfortunately, the AM detectors supplied with most modulation monitors do not provide a good enough match to be useful for this measurement. Precision envelope detectors are available that present a good match (30dB return loss or 1.06:1 VSWR) to the sampling line.

MINIMUM SYNCHRONOUS AM VERSUS EFFICIENCY

VHF amplifiers often exhibit a somewhat unusual characteristic when tuning for maximum efficiency. The highest efficiency operating point does not exactly coincide with the lowest plate current because the power output continues to rise for a while on the inductive side of resonance coming out of the dip in plate current. If the amplifier is tuned exactly to resonance, the plate load impedance will be purely resistive and the load line will be linear. As the output circuit is tuned to the inductive side of resonance, the plate load impedance becomes complex and the load line becomes elliptical instead of linear since the plate current and plate voltage are no longer in phase. Apparently best efficiency occurs when the phase of the instantaneous plate voltage slightly leads the plate current.

The point of minimum synchronous AM occurs closer to the minimum plate current rather than peak efficiency, so there is a compromise between good synchronous AM and best efficiency. A properly designed and neutralized transmitter should be able to achieve minimum synchronous AM without giving up more than about 3% in efficiency.

FINE TUNING TO MINIMIZE CROSSTALK INTO THE SCA

For stations employing a 67kHz SCA, transmitter tuning becomes very critical to minimizing crosstalk into the SCA. After tuning for minimum synchronous AM, modulate one channel only on the stereo generator to 100% with a 4.5 kHz tone. This will place the lower second harmonic (L-R) stereo sideband on top of the 67 kHz SCA. Activate the SCA at normal injection level without modulation on the SCA. Fine tune the transmitter for minimum output from the SCA demodulator. This adjustment can also be made by listening to the residual demodulated SCA audio while an unmodulated SCA and normal stereo programming are being broadcast.

COMPOSITE BASEBAND SPECTRUM ANALYSIS

Another more sophisticated method for fine tuning the transmitter is to directly observe the effects of tuning on distortion products within the composite baseband. These measurements require a stereo generator, a low frequency spectrum analyzer, and a precision demodulator. Crosstalk into the SCA can be directly measured independent of an SCA demodualtor by this method.

TUNING SENSITIVITIES

In any of these tests, the input tuning is frequently more critical than the output tuning. This is because the impedance match into the input capacitance of the grid becomes the bandwidth limiting factor. Even though the amplitude response appears flattened when the grid is heavily driven, the phase response has a serious effect on the higher order FM sidebands.

TEST SET-UP FOR SYNCHRONOUS AM AND COMPOSITE BASEBAND SPECTRUM MEASUREMENTS

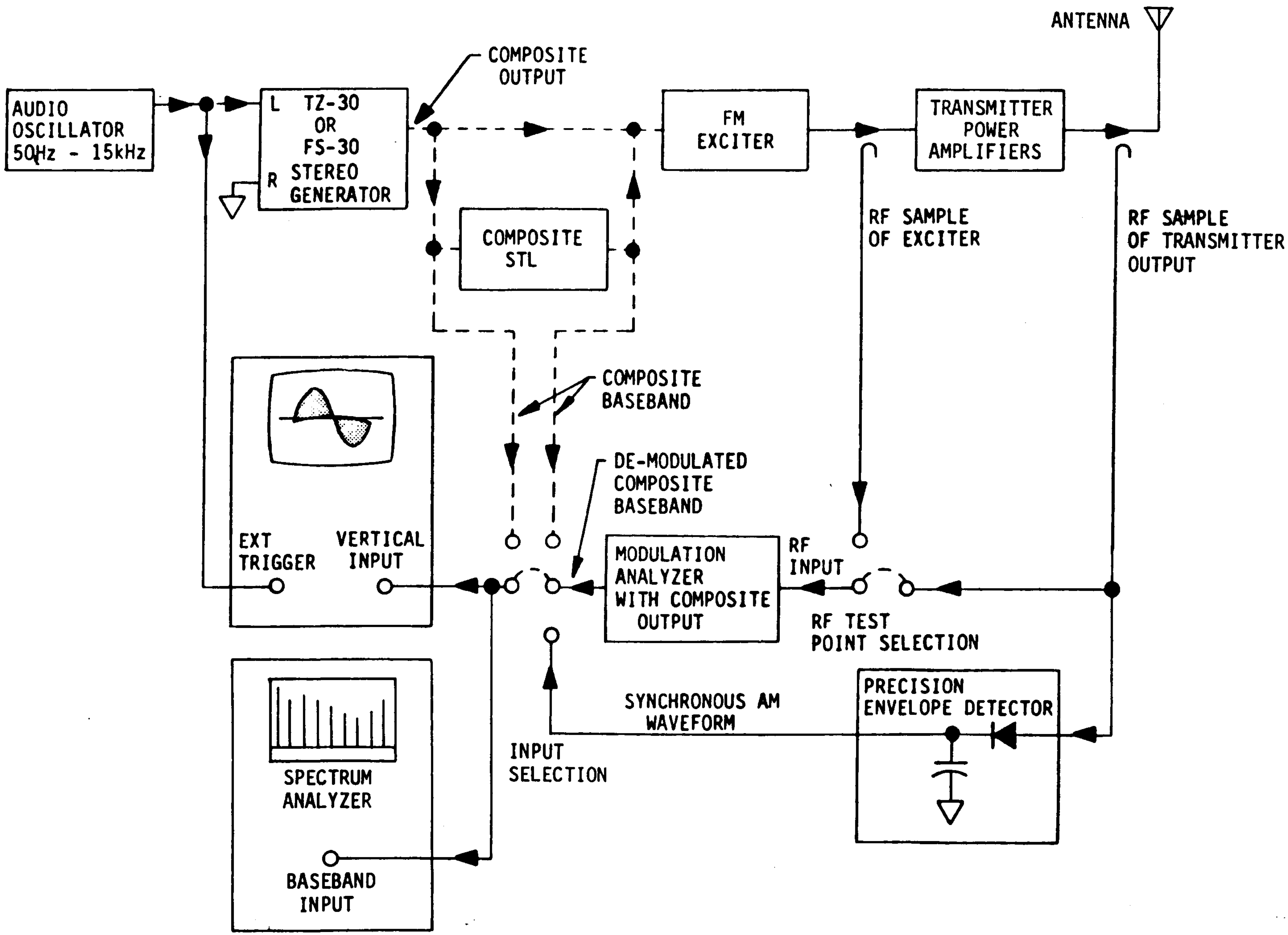

FIGURE 5

TEST EQUIPMENT SETUP

Figure-5 illustrates a typical test equipment setup and shows a block diagram of the required test equipment for making both synchronous AM and composite waveform measurements. A low frequency (10 Hz to 200 kHz) spectrum analyzer is used to determine the amount and location of distortion products added to the baseband signal as it passes through each stage of the overall system. Note that the composite baseband can be checked at various points along the transmission path in order to verify the performance and distortion contribution of each subsystem. The modulation monitor or modulation analyzer used to demodulate the RF to composite baseband must have a highly linear pulse counting discriminator in order to avoid the introduction of distortion products during the demodulation process.

A precision envelope detector with high return loss (low input VSWR) is included in the test set-up so that accurate synchronous AM waveforms can be observed while tuning the FM transmitter.

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The author holds three U.S. Patents for electronic designs utilized in broadcast equipment and is a registered professional engineer in the State of Illinois. He has authored numerous technical papers, is an associate member of the AFCCE, and a senior member of the IEEE.

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