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FM Broadcast Transmitters

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HISTORY OF FM BROADCASTING[2]

Although the principle of frequency modulation has been known for a long time, the advantages for broadcasting were not generally realized until the 1930's, largely as a result of the extensive FM development work done by Major Edwin H. Armstrong.

Among the advantages of FM are freedom from static and fading, and the ability of an FM receiver to capture the stronger of two signals transmitted on the same carrier frequency.

In 1940, following extensive public hearings, the Commission established the FM Broadcast Service and set aside 40 channels in the 42 to 50 MHz band with commercial operation scheduled to begin January 1, 1941. Although World War II stopped all nonmilitary radio construction, more than 40 FM stations continued to serve some 400,000 receivers. To eliminate the interference problems resulting from skywave reflection in the prewar FM band, the Commission moved the FM Broadcast Service to the 88 to 108 MHz band in 1945, thereby increasing the number of available channels to 100. However, the expected growth of FM broadcasting did not materialize. Since conversion of prewar FM receivers to the new band was not practical, purchase of a new receiver was the only way to receive the new FM stations. Television appeared to offer much more to the consumer than FM radio, since most FM stations merely duplicated the programming of an affiliated AM station. Despite the potential for a quality broadcast service, there was little public demand for new FM receivers and virtually no public reaction when FM stations dropped popular programs from their schedule or were off the air due to equipment failures. It is not surprising, therefore, that in May 1950, there had been only 16 new FM license applications during the previous 15 months in which 259 FM stations ceased operations.

During 1949 and 1950, some 35 FM stations began transit radio and storecasting experiments in an effort to make FM broadcasting pay. Although these "broadcasts" represented a backward step in programming standards, they appeared a desirable alternative to letting the FM Broadcast Service expire. These early ventures in the use of FM to provide nonbroadcast services to subscribers did not use multiplex techniques and consequently could not be received on all FM receivers. However, the use of a "beep" tone permitted the volume level of certain receivers to be turned up or down in accordance with the requirements of the particular type of subscriber. Beginning in 1955, the Commission permitted FM licensees to engage in certain types of nonbroadcast services on a multiplexed basis under a Subsidiary Communications Authorization (SCA). Multiplexed operation permits the reception of this service on special receivers in the stores, factories, etc., of subscribers without interference to the regular FM broadcast program. Our present FM stereo system is an extension of these multiplex techniques, and provides for the inclusion of one SCA channel in addition to the stereo transmission.

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[2]This section on history is extracted with permission of the author from the paper "FCC Regulations Governing the Audio Fidelity Characteristics of FM Broadcast Equipment," by John T. Robinson and L. Glenn Whipple of the FCC, which was presented October 18, 1967, at the 33rd Convention of the Audio Engineering Society, July 1968, Vol. 16, No. 3.

It should be pointed out that the Commission considers the unauthorized reception and use of these private subscription services to be a violation of Section 605 of the Communications Act. Such violations will be referred to the Department of Justice where appropriate and may subject the user to the criminal penalties provided for in the Communications Act.

Considerations in Determining Whether to Authorize Stereo Operation

The first clear showing of widespread public interest in FM multiplex stereo broadcasting was expressed in 1958 in an FCC Rule-Making proceeding which was concerned primarily with the uses of multiplexing under SCAs. Also in 1958 and 1959, the FCC received several petitions to permit stereo broadcasting.

The FCC engineers felt that one of the first things to be done was to find out whether stereophonic reproduction of program material was really worthwhile; that is, whether it actually did improve the realism of the program from the standpoint of the listener. In pursuing this, the FCC reviewed published material by researchers including George W. Stewart, Dr. Harry F. Olson, Dr. Harvey Fletcher and others, who investigated the various factors involved in localization of a sound by a listener, and published the results of much study and experimentation. The Commission and high fidelity enthusiasts everywhere are indebted to these gentlemen for their pioneering work in this field. After this study, several conclusions seemed appropriate:

1. The achievement of realism in reproduced sound requires the fulfillment of four fundamental conditions: first, the frequency range of the system must permit all of the audible components of the original sound to be reproduced; second, the volume range of the system must enable reproduction of the entire range of intensity of the sounds without noise or distortion; third, the reverberation characteristics of the original sound must be conveyed to the listener; and fourth, the spatial impressions must be conveyed to the listener. A monaural or monophonic system cannot satisfy this fourth requirement.

2. While a stereo system employing three or more channels is generally conceded to be superior to a two-channel system in reproduction of speech and moving sound sources, a two-channel system can give good satisfaction for orchestral reproduction.

3. The frequency range of each channel of the system adopted should be as good as that required by present FM broadcast standards, and the frequency-response characteristics should be as alike as possible in the channels.

Therefore, it seemed desirable to go ahead with the study of stereo systems for FM broadcast stations.

Adoption of Stereophonic Broadcasting in the United States

The United States system for FM multiplex stereo transmission was adopted by the FCC in 1961. The choice of systems followed a lengthy rule-making proceeding and study. A considerable amount of technical information and field test data for several proposed systems were provided to the FCC by an EIA committee, the National Stereophonic Radio Committee (NSRC). Engineers from equipment manufacturers, broadcasters, record manufacturers, and the FCC took part in the deliberations of the committee and the field tests which it conducted, all of which spanned a period of more than two years. During this period, it was necessary for FCC engineers to study and analyze many proposed systems. Some of the proposed systems were complete with signal specifications and equipment, while others were merely suggestions unaccompanied by engineering analysis or equipment designs. Still other systems or schemes were proposed and later dropped by their proponents in favor of modified or improved versions. All of this was reduced to six systems which were field tested by the National Stereophonic Radio Committee in the summer of 1960 using the transmitting facilities of station KDKA-FM, Pittsburgh, Pennsylvania, with receivers at Uniontown, Pennsylvania. The US system was adopted after a study of the field test results, together with an analysis of the theoretical capabilities of the systems tested.

Criteria Met by the US System

The system selected was found capable of meeting these important criteria:

1. Audio response of 50 to 15,000 Hz is preserved in both output channels.
2. Signal-to-noise ratios in both audio output channels are equal.
3. The information present in both input channels is reproduced in monophonic receivers.
4. Degradation in signal-to-noise ratio as received by monophonic receivers is minimal.
5. Electrical separation is maintained between the stereo channels throughout the audio frequency range.

FEATURES OF FM

Reduced Noise

The 88 to 108 MHz FM broadcast band is relatively free of atmospheric and other noise interference. Emission at these frequencies is not propagated great distances by ionospheric refraction as it is in the 550 to 1600 kHz AM band. Therefore, noise from lightning discharges is limited to substantially line-of-sight distances and is vastly lower and almost negligible. Man-made noise is a far greater source of noise, particularly in urban areas. The level of man-made noise falls off at increasing frequencies so that the microvolts-per-meter noise level is on the order of one-tenth as great in the FM band as in the AM band.

In addition, FM has an improvement factor compared to AM that is proportional to the frequency deviation ratio. This factor is illustrated in Fig. 1. There is a sharp threshold in signal level above which noise and interference are suppressed, which results in an improved S/N ratio. This same effect causes a weaker FM signal on the same channel to be suppressed, resulting in greatly reduced cochannel interference.

For greater noise reduction, pre-emphasis is employed whereby the audio frequency components above about 2.1 kHz are boosted in amplitude 6 dB per octave before being applied to the modulator. Flat frequency response is restored in the receiver by attenuating the higher frequencies the same amount they were boosted in the transmitter. High frequency components of noise are attenuated, resulting in greatly reduced background noise. This is discussed in more detail under FM Theory.

The net result of the above factors is the attainability of a much better signal-to-noise ratio. The lower background noise means that a signal of higher quality and wider dynamic range can be enjoyed.

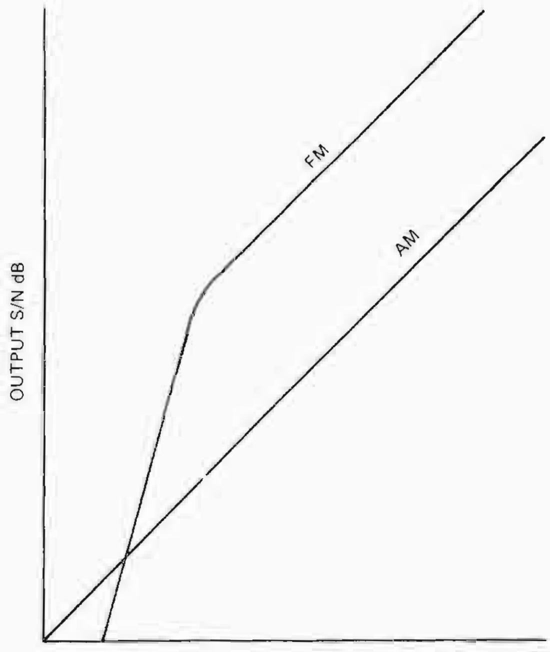


Fig. 1. FM improvement factor.

High Fidelity

Fidelity is defined as the degree to which a system, or a portion of a system, accurately reproduces at its output the essential characteristics of the signal which is impressed upon its input. The large market for hi-fi equipment is ample evidence that the public enjoys high-quality reproduction. Many individuals spend a great deal of money to have high-quality equipment in their homes.

Uniform frequency response over the audible range of at least 50 Hz to 15 kHz, very low amplitude distortion (harmonic and intermodulation), very low noise level, and good transient response (uniform time delay versus frequency) are necessary for hi-fi performance. The FM channel authorizations provide for adequate audio frequency range and a low-noise radio path. The rest of the performance is a matter of equipment design. It is much more feasible to design hi-fi characteristics into FM broadcast transmitters than AM broadcast transmitters. The FCC, therefore, has established minimum performance standards that assure hi-fi performance. Transmitter manufacturers strive to produce transmitters that exceed these minimum standards as far as practical, and broadcast stations strive to maintain the maximum performance capability of their equipment to provide truly hi-fi programs for the listener.

Stereophonic Transmission

A higher level of realism and listener enjoyment is provided by stereophonic transmission. Again, the wide channel allocations and inherent nature of FM permitted development of a practical stereo broadcasting system. This provides a means for the broadcast industry to provide the public with the same quality of hi-fi that they have available on stereo records and tape.

SCA

The wide channel bandwidth authorized for FM broadcasting makes it feasible to multiplex one or two subsidiary (SCA) channels together with the main transmission. Degradation of the main signal is kept small by limiting the percentage of modulation allocated to the SCA channels to 30 percent with monophonic broadcasting and 10 percent with stereophonic broadcasting. SCA provides an important source of revenue to many stations as well as a useful service to the community.

FCC TRANSMISSION STANDARDS

Some of the FCC Rules and Regulations covering transmitter performance are reproduced here to show the basic requirements. Because they are subject to change, an updated set of Rules and Regulations should be consulted regarding matters of importance.

73.254 Required Transmitter Performance

(a) The construction, installation, operation and performance of the FM broadcast transmitting system shall be in accordance with 73.317.

(b) The licensee of each FM broadcast station shall make equipment performance measurements at least once each calendar year: Provided, however, That the dates of completion of successive sets of measurements shall be no more than fourteen months apart. One set of measurements shall be made during the four-month period preceding the filing date of the application for renewal of station license. Equipment performance measurements shall be made with equipment adjusted for normal program operation and shall include all circuits between the main studio microphone terminals and the antenna circuit, including telephone lines, pre-emphasis circuits and any equalizers employed, except for microphones, and without compression if a compression amplifier is installed. The measurement program shall yield the following information:

(1) Audio frequency response from 50 to 15,000 Hz for approximately 25, 50 and 100 percent modulation. Measurements shall be made on at least the following audio frequencies: 50, 100, 400, 1000, 5000, 10,000 and 15,000 Hz. The frequency response measurements should normally be made without de-emphasis; however, standard 75 microsecond de-emphasis may be employed in the measuring equipment or system provided the accuracy of the de-emphasis circuit is sufficient to insure that the measured response is within the prescribed limits.

(2) Audio frequency harmonic distortion for 25, 50 and 100 percent modulation for the fundamental frequencies of 50, 100, 400, 1000, and 5000 Hz. Audio frequency harmonics for 100 percent modulation for fundamental frequencies of 10,000 and 15,000 Hz. Measurements shall normally include harmonics to 30,000 Hz. The distortion measurements shall be made employing 75 microsecond de-emphasis in the measuring equipment or system.

(3) Output noise level (frequency modulation) in the band of 50 to 15,000 Hz in decibels (dB) below the audio frequency level representing a frequency swing of 75 kHz. The noise measurements shall be made employing 75 microsecond de-emphasis in the measuring equipment or system.

(4) Output noise level (amplitude modulation) in the band of 50 to 15,000 Hz in dB below the level representing 100 percent amplitude modulation. The noise measurements shall be made employing 75 microsecond de-emphasis in the measuring equipment or system.

(c) The data required by paragraph (b) of this section, together with a description of instruments and procedure signed by the engineer making the measurements, shall be kept on file at the transmitter and retained for a period of two years, and shall be made available during that time upon request to any duly authorized representative of the Federal Communications Commission.

73.267 Operating Power: Determination and Maintenance

(a) *Determination.* The operating power of each station shall be determined by either the direct or indirect method.

(1) Using the direct method, the power shall be measured at the output terminals of the transmitter while operating into a dummy load of substantially zero reactance and a resistance equal to the transmission line characteristic impedance. The transmitter shall be unmodulated during this measurement. If electrical devices are used to determine the power output, such devices shall permit determination of this power to within an accuracy of ±5 percent of the electrical indicating instrument of the device. If temperature and coolant flow indicating devices are used to determine the power output, such devices shall permit determination of this power to within an accuracy of 4 percent of measured average power output. During this measurement the direct plate voltage and current of the last radio stage and the transmission line meter shall be read and compared with similar readings taken with the dummy load replaced by the antenna. These readings shall be in substantial agreement.

(2) Using the indirect method, the operating power is the product of the plate voltage (E_P) and the plate current (I_P) of the last radio stage, and an efficiency factor, F as follows:

$$\text{Operating power} = E_P \times I_P \times F$$

(3) The efficiency factor, F, shall be established by the transmitter manufacturer for each type of transmitter for which he submits data to the Commission, over the entire operating range of powers for which the transmitter is designed, and shall be shown in the instruction books supplied to the customer with each transmitter. In the case of composite equipment, the factor F shall be furnished to the Commission with a statement of the basis used in determining such factor.

(b) *Maintenance.*

(1) The operating power shall be maintained as near as practicable to the authorized power and shall not be less than 90 percent nor greater than 105 percent of authorized power except as indicated in paragraph (c) of this section.

(2) When determined by the direct method, the operating power of the transmitter shall be monitored by a transmission line meter which reads proportional to the voltage, current, or power at the output terminals of the transmitter, the meter to be calibrated at intervals not exceeding 6 months. The calibration shall cover, as a minimum, the range from 90 to 105 percent of authorized power, and the meter shall provide clear indications which will permit maintaining the operating power within the prescribed tolerance or the meter shall be calibrated to read directly in power units.

(c) *Reduced power.* In the event it becomes technically impossible to operate with authorized power, the station may be operated with reduced power for a period of 10 days or less without further authority of the Commission: Provided, That the Commission and the Engineer in charge of the radio district in which the station is located shall be immediately notified in writing if the station is unable to maintain the minimum operating schedule (specified in 73.261) with authorized power and shall be subsequently notified upon resumption of operation with authorized power.

73.268 Modulation

The percentage of modulation shall be maintained as high as possible consistent with good quality of transmission and good broadcast practice. In no case is it to exceed 100 percent on peaks of frequent recurrence. Generally, it should not be less than 85 percent on peaks of frequent recurrence; but where necessary to avoid objectionable loudness modulation may be reduced to whatever level is necessary, even if the resulting modulation is substantially less than 85 percent on peaks of frequent recurrence.

73.269 Frequency Tolerance

The center frequency of each FM broadcast station shall be maintained within 2,000 cycles per second of the assigned center frequency.

73.310 Definitions

Center frequency. The term "center frequency" means:

(1) The average frequency of the emitted wave when modulated by a sinusoidal signal.

(2) The frequency of the emitted wave without modulation.

Effective radiated power. The term "effective radiated power" means the product of the antenna power (transmitter output power less transmission line loss) times:

(1) the antenna power gain, or

(2) the antenna field gain squared.

Where circular or elliptical polarization is employed, the term effective radiated power is applied separately to the horizontal and vertical components of radiation. For allocation purpose, the effective radiated power authorized is the horizontally polarized component of radiation only.

Frequency modulation. A system of modulation where the instantaneous radio frequency varies in proportion to the instantaneous amplitude of the modulating signal (amplitude of modulating signal to be measured after pre-emphasis, if used) and the instantaneous radio frequency is independent of the frequency of the modulating signal.

Frequency swing. The instantaneous departure of the frequency of the emitted wave from the center frequency resulting from modulation.

Multiplex transmission. The term "multiplex transmission" means the simultaneous transmission of two or more signals within a single channel. Multiplex transmission as applied to FM broadcast stations means the transmission of facsimile or other signals in addition to the regular broadcast signals.

Percentage modulation. The ratio of the actual frequency swing to the frequency swing defined as 100 percent modulation, expressed in percentage. For FM broadcast stations, a frequency swing of ±75 kHz is defined as 100 percent modulation.

(a) *Stereophonic broadcasting.*

Cross-talk. An undesired signal occurring in one channel caused by an electrical signal in another channel.

FM stereophonic broadcast. The transmission of a stereophonic program by a single FM broadcast station utilizing the main channel and a stereophonic subchannel.

Left (or right) signal. The electrical output of a microphone or combination of microphones placed so as to convey the intensity, time, and location of sounds originating predominately to the listener's left (or right) of the center of the performing area.

Left (or right) stereophonic channel. The left (or right) signal as electrically reproduced in reception of FM stereophonic broadcasts.

Main channel. The band of frequencies from 50 to 15,000 Hz which frequency-modulate the main carrier.

Pilot subcarrier. A subcarrier serving as a control signal for use in the reception of FM stereophonic broadcasts.

Stereophonic separation. The ratio of the electrical signal 'caused in' the right (or left) stereophonic channel to the electrical signal caused in the left (or right) stereophonic channel by the transmission of only a right (or left) signal.

Stereophonic subcarrier. A subcarrier having a frequency which is the second harmonic of the pilot subcarrier frequency and which is employed in FM stereophonic broadcasting.

Stereophonic subchannel. The band of frequencies from 23 to 53 kHz per second containing the stereophonic subcarrier and its associated sidebands.

73.317 Transmitters and Associated Equipment

(a) *Electrical performance standards.* The general design of the FM broadcast transmitting system (from input terminals of microphone preamplifier, through audio facilities at the studio, through lines or other circuits between studio and transmitter, through audio facilities at the transmitter, and through the transmitter, but excluding equalizers for the correction of deficiencies in microphone response) shall be in accordance with the following principles and specifications:

(1) The transmitter shall operate satisfactorily in the operating power range with a frequency swing of 75 kHz, which is defined as 100 percent modulation.

(2) The transmitting system shall be capable of transmitting a band of frequencies from 50 to 15,000 Hz. Pre-emphasis shall be employed in accordance with the impedance-frequency characteristic of a series inductance-resistance network having a time constant of 75 microseconds. (See Fig. 2 of 73.333.) The deviation of the system response from the standard pre-emphasis curve shall lie between two limits as shown in Fig. 2 of 73.333. The upper of these limits shall be uniform (no deviation) from 50 to 15,000 Hz. The lower limit shall be uniform from 100 to 7,500 Hz, and 3 dB below the upper limit; from 100 to 50 Hz the lower limit shall fall from the 3 dB limit at a uniform rate of 1 dB per octave (4 dB at 50 Hz); from 7,500 to 15,000 c/s the lower limit shall fall from the 3 dB limit at a uniform rate of 2 dB per octave (5 dB at 15,000 Hz).

(3) At any modulation frequency between 50 and 15,000 Hz and at modulation percentages of 25, 50, and 100 percent, the combined audio frequency harmonics measured in the output of the system shall not exceed the root-mean-square values given in the following table:

Modulating frequency:	*Distortion percent*
50 to 100 Hz	3.5
100 to 7,500 Hz	2.5
7,500 to 15,000 Hz	3.0

(i) Measurements shall be made employing 75 microsecond de-emphasis in the measuring equipment and 75 microsecond pre-emphasis in the transmitting equipment, and without compression if a compression amplifier is employed. Harmonics shall be included to 30 kHz.

(ii) It is recommended that none of the three main divisions of the system (transmitter, studio to transmitter circuit, and audio facilities) contribute over one-half of these percentages since at some frequencies the total distortion may become the arithmetic sum of the distortions of the divisions.

(4) The transmitting system output noise level (frequency modulation) in the band of 50 to 15,000 Hz shall be at least 60 dB below 100 percent modulation (frequency swing of ±75 Hz). The measurement shall be made using 400 cycle modulation as a reference. The noise-measuring equipment shall be provided with standard 75 microsecond de-emphasis; the ballistic characteristics of the instrument shall be similar to those of the standard VU meter.

(5) The transmitting system output noise level (amplitude modulation) in the band of 50 to 15,000 Hz shall be at least 50 dB below the level representing 100 percent amplitude modulation. The noise-measuring equipment shall be provided with standard 75-microsecond de-emphasis; the ballistic characteristics of the instrument shall be similar to those of the standard VU meter.

(6) Automatic means shall be provided in the transmitter to maintain the assigned center frequency within the allowable tolerance (±2,000 Hz).

(7) The transmitter shall be equipped with suitable indicating instruments for the determination of operating power and with other instruments as are necessary for proper adjustment, operation, and maintenance of the equipment (see 73.320).

(8) Adequate provision shall be made for varying the transmitter output power to compensate for excessive variations in line voltage or for other factors affecting the output power.

(9) Adequate provision shall be provided in all component parts to avoid overheating at the rated maximum output power.

(10) Means should be provided for connection and continuous operation of approved frequency and modulation monitors.

(11) If a limiting or compression amplifier is employed, precaution should be maintained in its connection in the circuit due to the use of pre-emphasis in the transmitting system.

(12) Any emission appearing on a frequency removed from the carrier by between 120 kHz and 240 kHz, inclusive, shall be attenuated at least 25 dB below the level of the unmodulated carrier. Compliance with this specification will be deemed to show the occupied bandwidth to be 240 kHz or less.

(13) Any emission appearing on a frequency removed from the carrier by more than 240 kHz and up to and including 600 kHz shall be attenuated at least 35 dB below the level of the unmodulated carrier.

(14) Any emission appearing on a frequency removed from the carrier by more than 600 kHz shall be attenuated at least $43 + 10 \, \mathrm{Log}_{10}$ (Power, in watts) decibels below the level of the unmodulated carrier, or 80 decibels, whichever is the lesser attenuation.

73.319 Subsidiary Communications Multiplex Operations: Engineering Standards

(a) Frequency modulation of SCA subcarriers shall be used.

(b) The instantaneous frequency of SCA subcarriers shall at times be within the range 20 to 75 kHz: Provided, however, That when the station is engaged in stereophonic broadcasting pursuant to 73.297, the instantaneous frequency of SCA subcarriers shall at all times be within the range 53 to 75 kHz.

(c) The arithmetic sum of the modulation of the main carrier by SCA subcarriers shall not exceed 30 percent: Provided, however, That when the station is engaged in stereophonic broadcasting pursuant to 73.297, the arithmetic sum of the modulation of the main carrier by the SCA subcarriers shall not exceed 10 percent.

(d) The total modulation of the main carrier, including SCA subcarriers, shall meet the requirements of 73.268.

(e) Frequency modulation of the main carrier caused by the SCA subcarrier operation shall, in the frequency range 50 to 15,000 Hz, be at least 60 dB below 100 percent modulation: Provided, however, That when the station is engaged in stereophonic broadcasting pursuant to 73.297, frequency modulation of the main carrier by the SCA subcarrier operation shall, in the frequency range 50 to 53,000 Hz, be at least 60 dB below 100 percent modulation.

73.322 Stereophonic Transmission Standards

(a) The modulating signal for the main channel shall consist of the sum of the left and right signals.

(b) A pilot subcarrier at 19,000 Hz plus or minus 2 Hz shall be transmitted that shall frequency modulate the main carrier between the limits of 8 and 10 percent.

(c) The stereophonic subcarrier shall be the second harmonic of the pilot subcarrier and shall cross the time axis with a positive slope simultaneously with each crossing of the time axis by the pilot subcarrier.

(d) Amplitude modulation of the stereophonic subcarrier shall be used.

(e) The stereophonic subcarrier shall be suppressed to a level less than one percent modulation of the main carrier.

(f) The stereophonic subcarrier shall be capable of accepting audio frequencies from 50 to 15,000 Hz.

(g) The modulating signal for the stereophonic subcarrier shall be equal to the difference of the left and right signals.

(h) The preemphasis characteristics of the stereophonic subchannel shall be identical with those of the main channel with respect to phase and amplitude at all frequencies.

(i) The sum of the side bands resulting from amplitude modulation of the stereophonic subcarrier shall not cause a peak deviation of the main carrier in excess of 45 percent of total modulation (excluding SCA subcarriers) when only a left (or right) signal exists; simultaneously in the main channel, the deviation when only a left (or right) signal exists shall not exceed 45 percent of total modulation (excluding SCA subcarriers).

(j) Total modulation of the main carrier including pilot subcarrier and SCA subcarriers shall meet the requirements of 73.268 with maximum modulation of the main carrier by all SCA subcarriers limited to 10 percent.

(k) At the instant when only a positive left signal is applied, the main channel modulation shall cause an upward deviation of the main carrier frequency; and the stereophonic subcarrier and its sidebands signal shall cross the time axis simultaneously and in the same direction.

(l) The ratio of peak main channel deviation to peak stereophonic subchannel deviation when only a steady state left (or right) signal exists shall be within plus or minus 3.5 percent of unity for all levels of this signal and all frequencies from 50 to 15,000 Hz.

(m) The phase difference between the zero points of the main channel signal and the stereophonic subcarrier sidebands envelope, when only a steady state left (or right) signal exists, shall not exceed plus or minus 3 degrees for audio, modulating frequencies from 50 to 15,000 Hz.

Note: If the stereophonic separation between left and right stereophonic channels is better than 29.7 dB at audio modulating frequencies between 50 and 15,000 Hz, it will be assumed that paragraphs (l) and (m) of this section have been complied with.

(n) Cross-talk into the main channel caused by a signal in the stereophonic subchannel shall be attenuated at least 40 dB below 90 percent modulation.

(o) Cross-talk into the stereophonic subchannel caused by a signal in the main channel shall be attenuated at least 40 dB below 90 percent modulation.

(p) For required transmitter performance, all of the requirements of 73.254 shall apply with the exception that the maximum modulation to be employed is 90 percent (excluding pilot subcarrier) rather than 100 percent.

(q) For electrical performance standards of the transmitter and associated equipment, the requirements of 73.317(a)(2), (3), (4), and (5) shall apply to the main channel and stereophonic subchannel alike, except that where 100 percent modulation is referred to, this figure shall include the pilot subcarrier.

FM MODULATION THEORY

In FM the instantaneous frequency (rate of change of phase) of the rf output wave differs from the carrier frequency by an amount proportional to the instantaneous value of the modulating wave. For example, consider a 100-MHz carrier wave FM modulated by a 1000-Hz audio tone and assume that 1-volt input causes ±20-kHz frequency deviation on the positive and negative audio tone peaks. If the audio input amplitude is increased to 2 volts, the peak deviation will become ±40 kHz, and will vary in sine-wave fashion from one peak deviation to the other and back again at the 1000-Hz rate. In FM broadcasting, the FCC has established that a frequency deviation of 75 kHz shall constitute 100 percent modulation.

An important term to understand in FM is modulation index. With a sinusoidal modulating wave, the modulation index

$$m = \frac{\text{frequency deviation}}{\text{modulating frequency}}$$

An FM rf output wave contains many sideband frequency components, theoretically an infinite number. They consist of pairs of sideband components spaced from the carrier frequency by multiples of the modulating frequency. When the modulation index is small (< 0.5) the second and higher order sidebands are small so that the output consists essentially of the carrier and the pair of first order sidebands. (See Fig. 2a.) The transmitter rf output power remains constant with modulation, so the power in the carrier is reduced by the amount of power in the sidebands. In other words, the sum of the squares of the carrier voltage amplitude and all of the sideband voltage amplitudes must equal the square of the unmodulated carrier amplitude.

As the modulation index (or signal level) is increased, the higher order sidebands become more prominent. The amplitude of the carrier and the sidebands can be expressed mathematically by the use of Bessel functions.

$e(t) =$	total rf output voltage
$+EJ_0(m)\cos\omega t$	carrier
$+EJ_1(m)\cos(\omega+\rho)t$	first order upper sideband
$-EJ_1(m)\cos(\omega-\rho)t$	first order lower sideband
$+EJ_2(m)\cos(\omega+2\rho)t$	second order upper sideband
$+EJ_2(m)\cos(\omega-2\rho)t$	second order lower sideband
$+J_3(m)\cos(\omega+3\rho)t$	third order upper sideband
$-J_3(m)\cos(\omega-3\rho)t$	third order lower sideband
------------------------	higher order sidebands

where

m is the modulation index,
ω is the carrier frequency, and
ρ is the modulating frequency.

The Bessel functions $J_0(m)$, etc., which express the amplitude of the various frequency components can be found in mathematical tables. Fig. 3 shows how the carrier and first eight pairs of sideband components vary with modulation index. (This is simply a plot of Bessel functions.)

In a monophonic FM broadcast transmitter, the modulation index can become very high. With a 50 Hz audio input signal of sufficient amplitude to produce 75 kHz deviation (corresponding to 100 percent modulation), the modulation index

$$m = \frac{75000}{50} = 1500$$

With 15,000 Hz input at 100 percent modulation, the modulation index

$$m = \frac{75000}{15000} = 5$$

Fig. 2b and 2c illustrate the frequency components present for modulation indexes of 5 and of 20. The number of significant sideband components becomes very large with large modulation indexes. The total bandwidth occupied extends beyond ±75 kHz from the carrier depending upon the modulating frequency. This

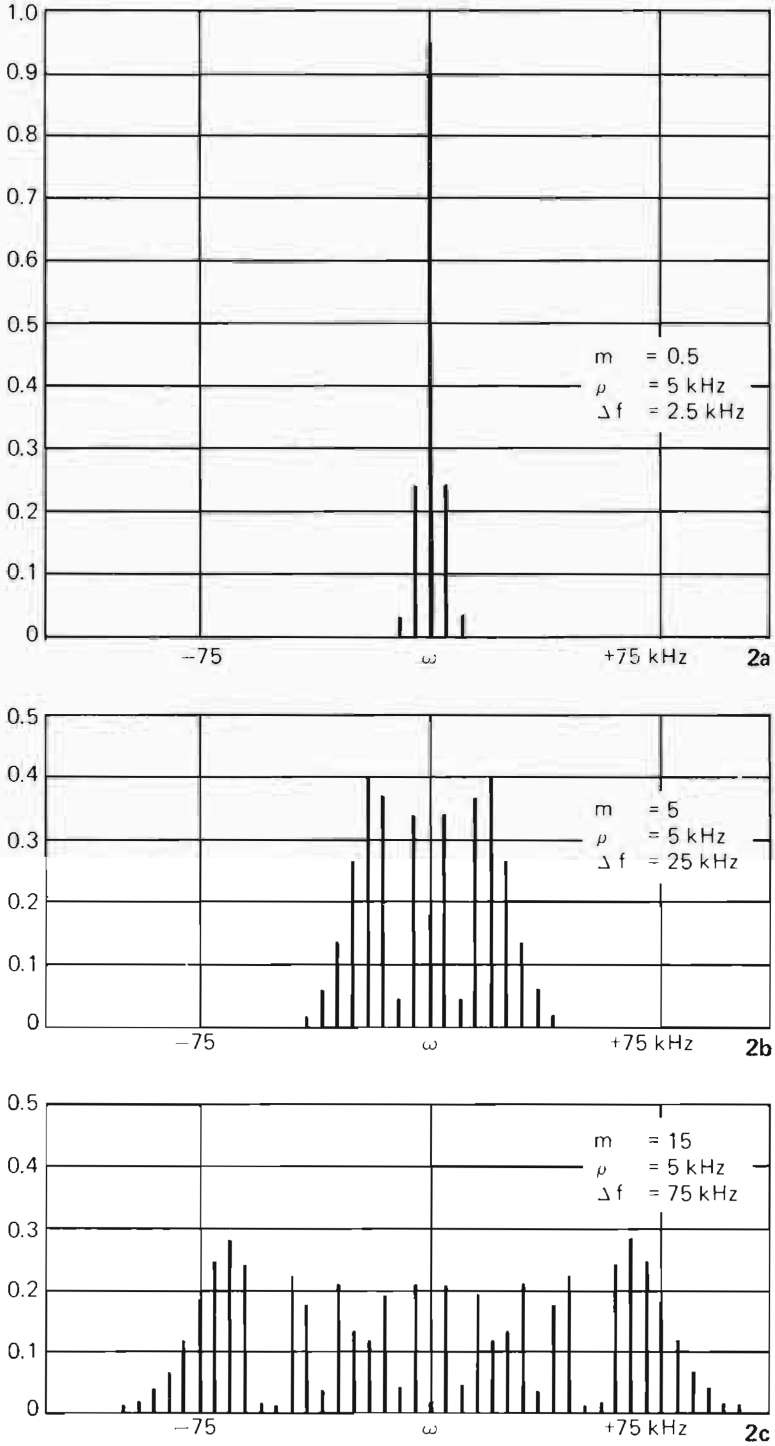


Fig. 2. RF spectrum with modulation indexes of 0.5, 5.0, and 20.0.

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 occupied band rather than appearing on discreet frequencies.

Referring to Fig. 3, note that the carrier amplitude goes to zero and reverses sign at several values of modulation index 2.4048, 5.5201, and 8.6537. This relationship can be used to measure

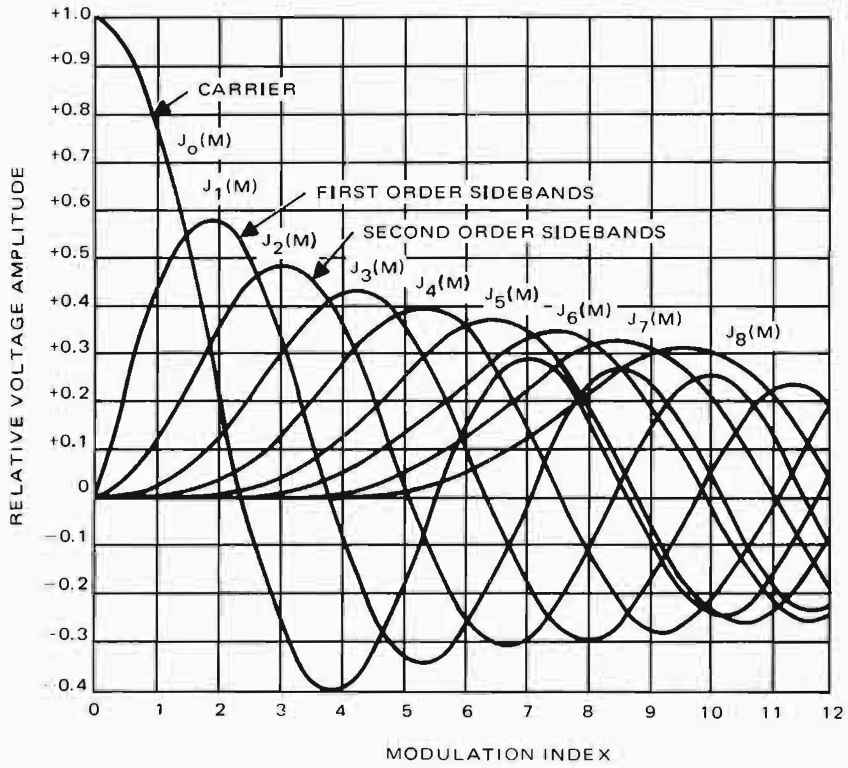


Fig. 3. Relationship of carrier and sideband amplitudes to modulation index.

frequency deviation. It we want to measure the audio input level required to achieve 75-kHz deviation, we can apply an audio tone of $\frac{75000}{8.6537}$ or 8,666 Hz and increase the audio level until the carrier disappears the third time. At this audio level the deviation is 75 kHz. The carrier amplitude detector must have sufficient selectivity to separate the carrier from the sidebands, of course. A listing of some of the more useful points of carrier disappearance is given in Table 1. This method can be used to check the accuracy of a modulation monitor, for example.

A frequency (or phase) modulated wave can be multiplied or divided, and this also multiplies or divides the frequency deviation and the modulation index.

TABLE 1

Modulation Indexes That Produce the First Seven Carrier and First Order Sideband Disappearances and the Corresponding Audio Modulating Frequencies That Produce These Same Disappearances When the Deviation Is 75 kHz

Disappearance	Modulation index		Freq. for 75 kHz dev.	
	Carrier	1st sideband	Carrier	1st sideband
1st	2.405	3.852	31,188	19,320
2nd	5.520	7.016	13,587	10,670
3rd	8.654	10.173	8,667	7,372
4th	11.792	13.323	6,360	5,629
5th	14.931	16.470	5,023	4,554
6th	18.071	19.616	4,150	3,823
7th	21.212	22.760	3,536	3,295

In PM, the modulating signal causes the *phase* of the carrier wave to vary according to the instantaneous amplitude of the modulating signal. There is a very simple but important relationship between PM and FM. If the audio frequency response is made to fall off 6 dB per octave across the entire audio band and is used to phase modulate a carrier, the resulting modulated output will be identical to that of a frequency modulated carrier. This principle was used in many FM broadcast transmitters prior to the advent of stereo broadcasting. The principal advantage was that the carrier frequency could be generated by a stable crystal oscillator. The amount of low distortion phase modulation was quite limited in most systems so it was necessary to start with a low crystal oscillator frequency and multiply it many times (such as 864) to achieve 75 kHz deviation with 50 Hz audio modulation. This technique has been abandoned in favor of direct FM in all new FM broadcast transmitter exciters designed to accommodate stereo transmission.

PRE-EMPHASIS

The standards adopted for FM broadcasting require the use of pre-emphasis. The standard pre-emphasis curve is defined as an ideal RC

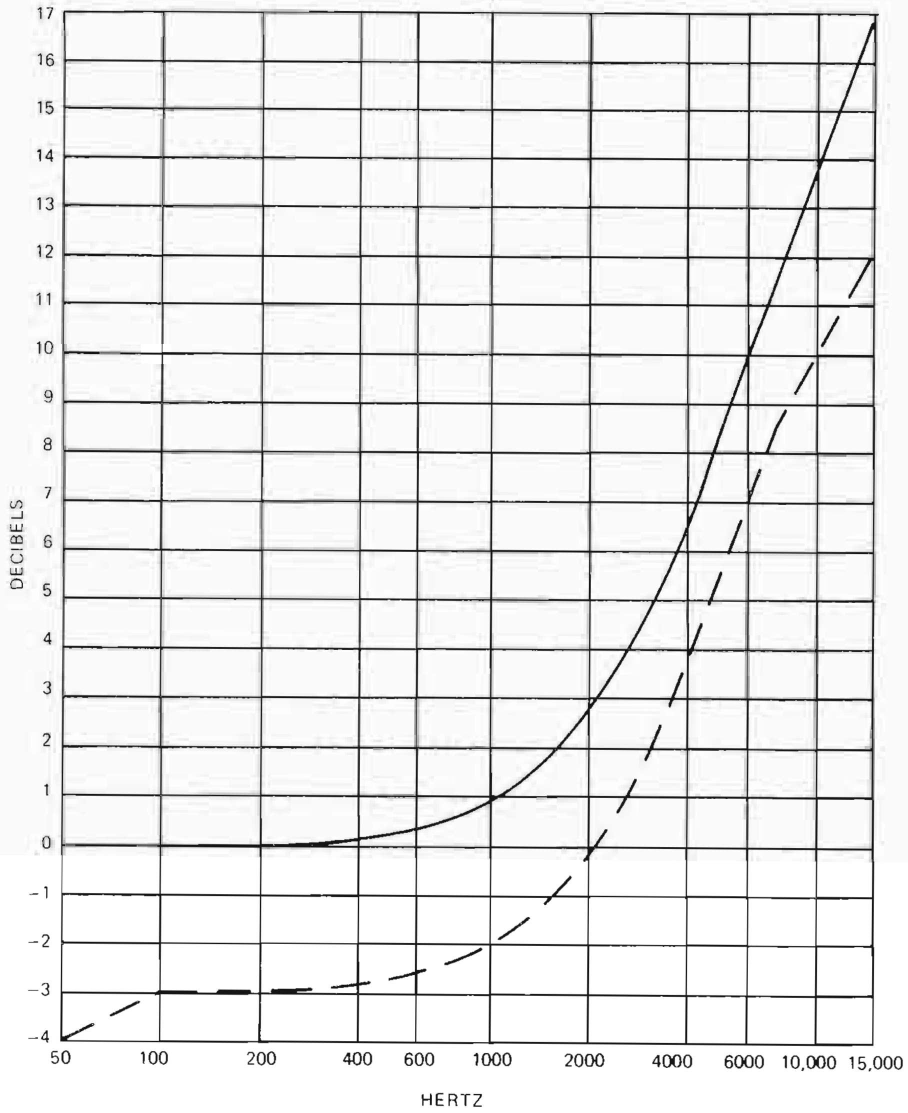


Fig. 4. Standard 75-microsecond pre-emphasis curve (solid line) and tolerance limits (solid and dashed lines).

network with a time constant of 75 microseconds. The 3-dB point is at

$$f = \frac{1}{2\pi RC} = \frac{1}{2\pi\, 75 \times 10^{-6}} = 2{,}122 \text{ Hz.}$$

The 75-microsecond curve and the tolerance allowed is shown in Fig. 4.

The reduction in receiver output noise due to the use of pre-emphasis in monophonic transmission is illustrated in Fig. 5. The noise voltage in a narrow band (for example, 1 Hz) increases directly with frequency, therefore, the power spectral density increases as the square of frequency as shown. When pre-emphasis is used, the noise voltage is attenuated above 2.1 kHz so that it remains constant with frequency. The power spectral density is, therefore, also constant above 2.1 kHz. The area between these curves represents the noise power that is removed by the use of pre-emphasis. This diagram indicates the importance of pre-emphasis for high-fidelity transmission because the high-frequency noise would be very much greater without it.

Pre-emphasis is practical because program energy tends to peak around 1 kHz and falls off fairly rapidly at the higher frequencies. For this reason, the higher frequencies can be boosted in amplitude without causing much increase in modulation level. There is some increase, however, so the net improvement due to pre-emphasis is the ratio of the areas under the two curves of the diagram less this small reduction in audio input level required to keep within the 100 percent modulation limit.

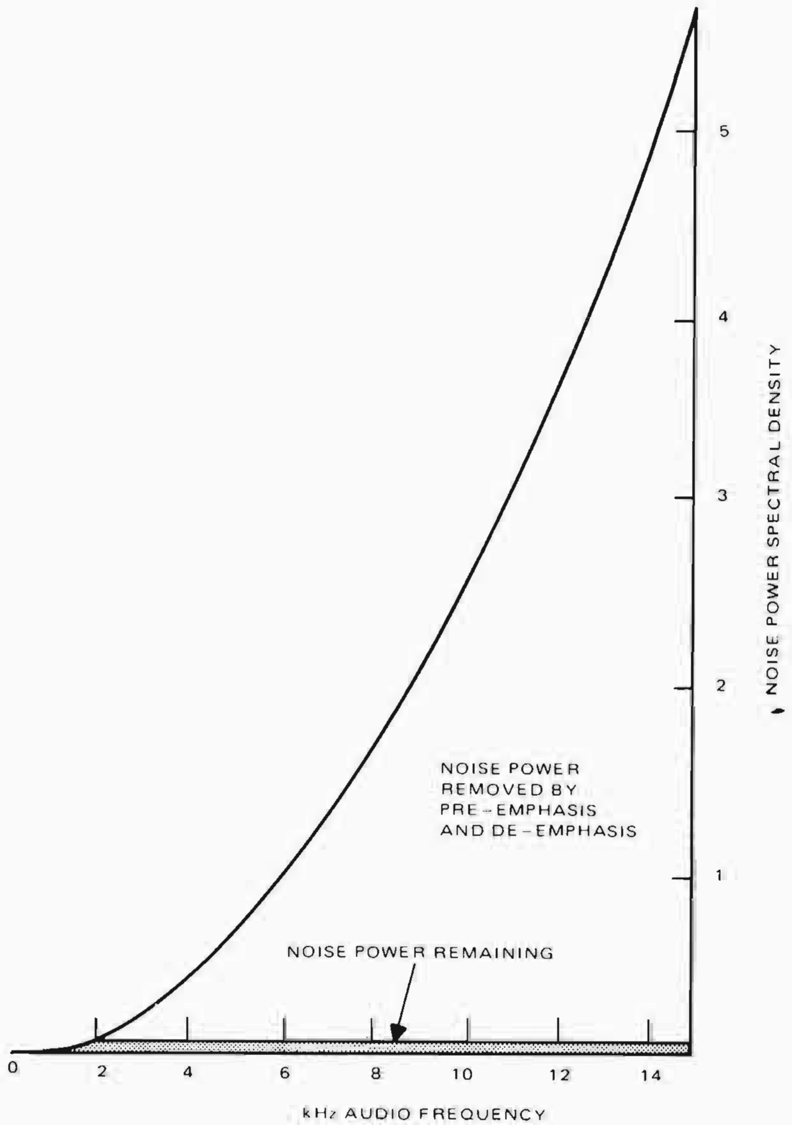


Fig. 5. Noise power spectral density before and after de-emphasis in receiver.

THE STEREO BASEBAND SIGNAL

Fig. 6 shows the composite baseband signal that is used to frequency modulate the carrier. (An SCA channel is also shown but will be left for later discussion.) The L and R (left and right) stereo input channels are added together to provide the basic modulation which is suitable for reception by monophonic FM receivers. The monophonic receivers use this L+R modulation in the 50 to 15,000 Hz range but discard the pilot carrier and L-R signals used for stereo.

For stereo reception an additional signal consisting of an L-R signal is needed. This is the same as the L+R except that the phase of the R channel is reversed. This L-R signal is converted to a double sideband suppressed carrier (DSBSC) signal centered on the subcarrier frequency of 38 kHz. The subcarrier is suppressed to avoid wasting modulation capability. It is necessary, however, to reinsert the 38 kHz subcarrier at the receiver in order to demodulate the DSBSC L-R signal. This inserted carrier must be on the exact frequency and very nearly in the exact phase relationship to the sidebands as exists with the signal generated in the exciter. Therefore, a pilot carrier is transmitted.

Since audio frequencies at 50 Hz and below are very close to the 38 kHz subcarrier frequency, it would be difficult to filter out a pilot carrier at that frequency. The detected pilot carrier would also have a better signal-to-noise ratio by 6 dB if its frequency were halved. For these reasons, a pilot carrier at 19 kHz (half of 38 kHz) is

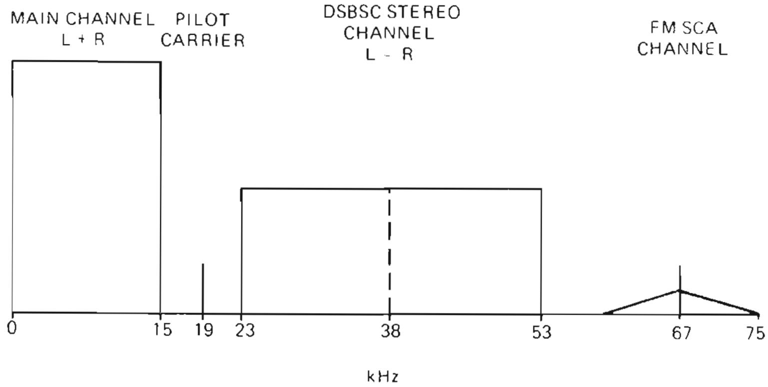


Fig. 6. Composite stereo baseband signal including an SCA channel.

transmitted at an 8 to 10 percent modulation level. This frequency is well removed from the required audio sidebands so that it can be readily separated from them and simply doubled to provide the desired subcarrier injection in the receiver.

In the receiver the demodulated L-R signal is combined with the L+R signal to obtain the separate L and R channels again.

$$(L+R) + (L-R) = 2\,L$$
$$(L+R) - (L-R) = 2\,R$$

For good stereo reception it is necessary that the L and R channels remain well separated (that is, audio in one channel shall not appear in the output of the other channel). The FCC requires 29.7 dB separation (which was about the best achievable when the rules were adopted). Exciters soon became available which were capable of better than 35 dB separation.

In order to maintain good separation, it is necessary that the amplitude and phase of the L+R and L-R paths be nearly identical and the phase of the pilot carrier correct.[3] The channel separation as a function of these three factors is given in the following equation.

separation dB =

$$20 \log_{10} \left[\frac{(\cos\theta + \frac{S}{M}\cos\phi)^2 + (\sin\theta)^2}{(\cos\theta - \frac{S}{M}\cos\phi)^2 + (\sin\theta)^2} \right]^{1/2}$$

where

M is the gain of the main L+R path
S is the gain of the stereo L-R path
ϕ is phase error of reinserted 38 kHz subcarrier that is twice the phase error of the 19 kHz pilot carrier
θ is difference in phase between L+R and L-R paths.

The effect of each alone upon the separation is shown in Fig. 7. In practice, loss of separation is due to some of each. Therefore, to achieve 35 dB separation, the amplitudes must match to about 1 percent and the phase to about 1° over the entire audio range from 50 Hz to 15 kHz. The phase of the pilot carrier should be within 4°. These are very stringent requirements. For this reason, designers keep the amount of circuitry in the separate L+R and L-R paths to a minimum.

Matrixing the L and R channels in this manner has a further advantage in that when the two transmission paths have unequal signal-to-noise ratios, the S/N on the L and R channels will be equal. This situation is less objectionable than having unequal S/N in the L and R channels. In the adopted system, the S/N is inherently much better in the L+R path than in the L-R path. This means that in weak signal conditions it may be possible to obtain good monophonic reception of a stereophonic broadcast even though stereophonic reception is poor. Some receivers are designed to switch to monophonic reception automatically in weak signal conditions.

An examination of an oscilloscope display of the stereo baseband signal will point up several important relationships. First consider a 1 kHz test tone applied to the L input only and pilot carrier turned off. Fig. 8a illustrates the ideal baseband signal. The baseline through the diagram will be a straight line for the ideal case of no distortion and perfect separation. Three frequency components are present: 1 kHz, 37 kHz, and 39 kHz. The latter two are each 1/2 the voltage amplitude of the first.

The picture will look the same when an R-only, 1 kHz tone is applied, although the phase of the two high-frequency components will be reversed.

[3]Lawrence C. Middlekamp, "Stereophonic Separation in Transmission" IEEE Transactions on Broadcasting Vol. BC-14, No. 3, Sept. 1968, and "Measurement of the Phase of the Stereophonic Subcarrier in FM Stereophonic Transmission." *Journal of the Audio Engineering Society*, April 1967, Vol. 15, No. 2.

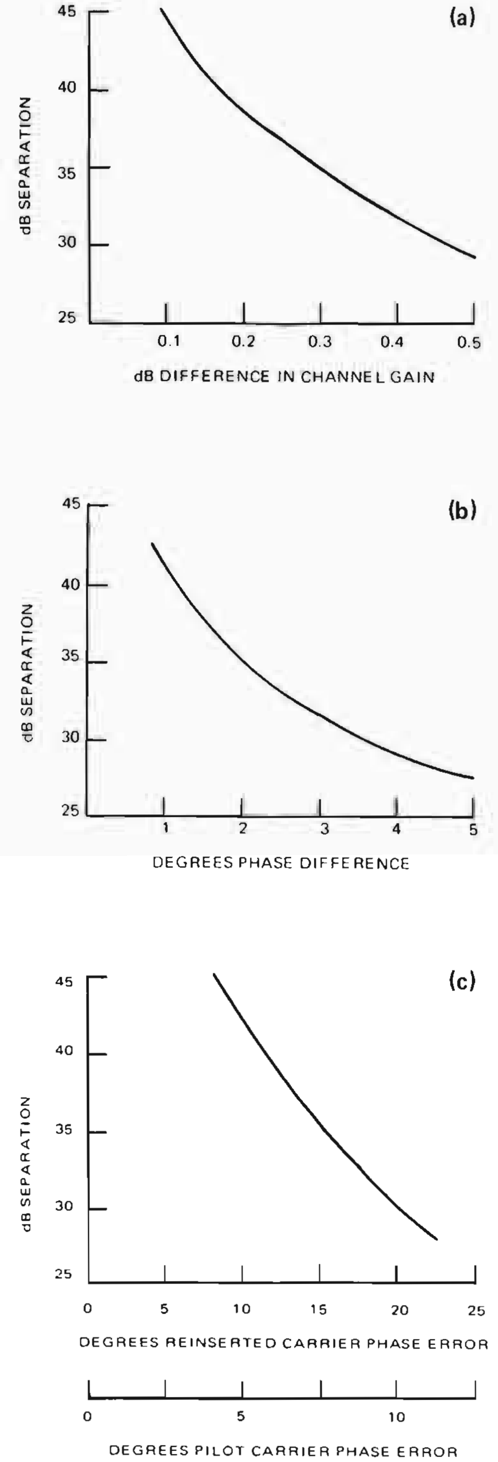


Fig. 7. Stereo separation versus (a) amplitude difference between main and stereo channels, (b) phase difference between main and stereo channels, and (c) error in phase of pilot or reinserted carrier.

Fig. 8b illustrates the case when the L and R inputs are identical. The only frequency present is 1 kHz because the signal in the L-R stereo channel is zero. Note that adding the R signal of the same amplitude as the original L signal does not change the peak amplitude.

Fig. 8c illustrates the case when L and R inputs are equal in amplitude but in phase opposition. The only components present are the DSBSC stereo channel components of 37 kHz and 39 kHz. Again note that the peak amplitude stays exactly the same. This means that the percentage modulation would also be the same because it is directly related to the peak amplitude of the baseband signal.

The baseband signal components have phase coherence so they add almost exactly in phase on signal peaks. This means that if the L and R audio input signals have no phase coherence the level transmitted in the L+R channel is one half or 6 dB less than that which would be transmitted by a monophonic transmitter.

Adding the pilot carrier to the above three cases gives the results shown in Fig. 9. The phase of the pilot carrier is such that a pilot carrier peak never occurs simultaneously with an L-R subchannel peak. As a result of this coherent phase relationship, the pilot carrier contribution to total modulation is not a direct arithmetic sum but depends upon the instantaneous L-R subchannel modulating level. For 90 percent subchannel modulation (L=-R) and 10 percent pilot carrier modulation—the total modulation is approximately 97.1 percent instead of 100 percent. (It is about the same for an L or R only test signal. To achieve 100 percent modulation, the audio must be increased about 0.25 dB.) For 90 percent main channel modulation (L=R) and 10 percent pilot carrier modulation, the total is 100 percent because in normal use there is no phase coherency between the signal and pilot carrier.

When program material is transmitted, the net loss in S/N to monophonic receiver going from monophonic to stereophonic transmission will probably be considerably less than the 6.25 dB loss in a single L or R test tone case but more than the 1 dB loss in the L=R case. It depends upon the L and R program input signals being somewhat more in phase rather than out of phase or noncoherent.

STEREO MATRIXING TECHNIQUES

There are two basic techniques used for obtaining the L+R and L-R signals. The simplest matrix circuit to understand is shown in Fig. 10a. The voltage outputs of the L and R transformers are simply added. Fig. 10b shows a bridge matrix technique which properly loads the transformers and allows the use of identical transformers. The other is a switching technique described in the following paragraphs.

It is a well-known fact in communications theory that the original signal can be recon-

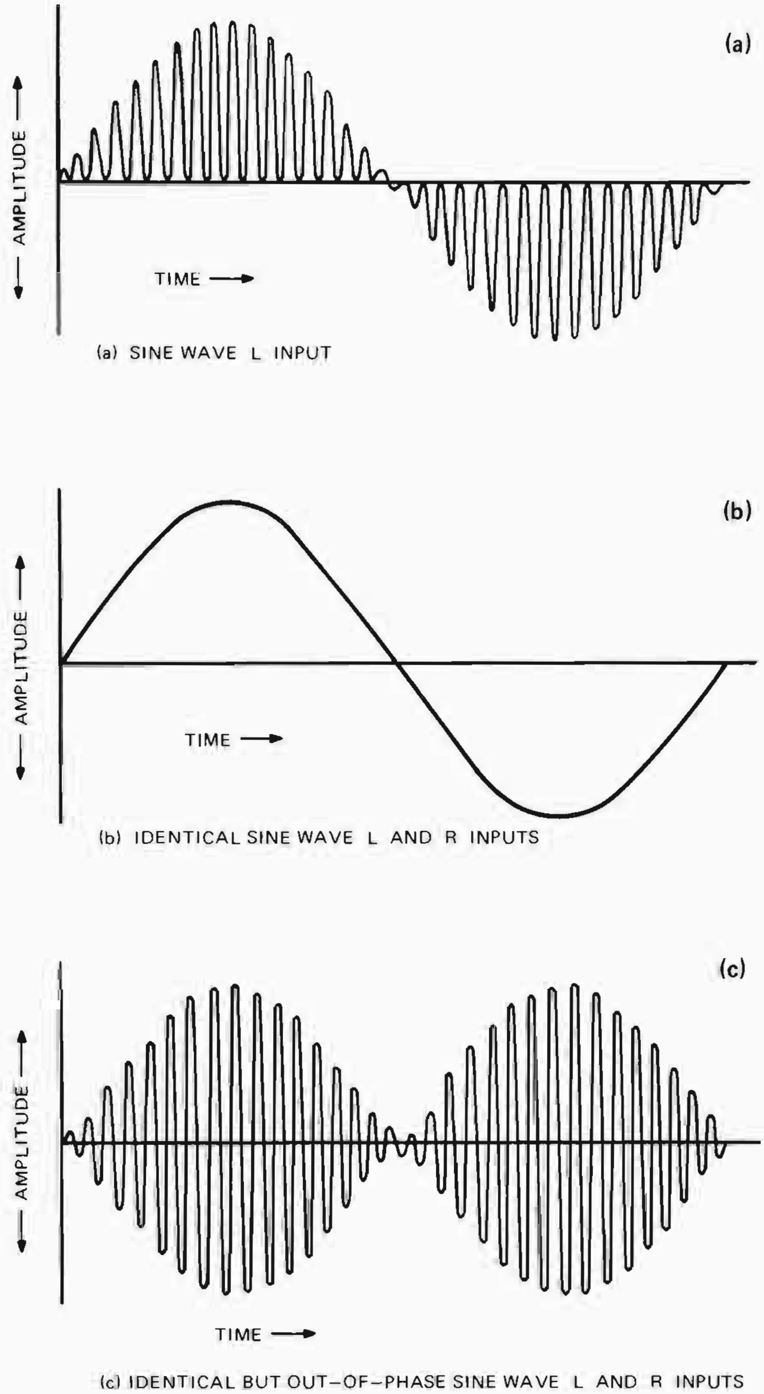


Fig. 8. Diagram of oscilloscope display of stereo baseband signal with (a) sine wave L input, (b) identical sine wave L and R inputs, and (c) identical but out-of-phase sine wave L and R inputs.

structed from samples of the signal amplitude, providing the samples are taken at a rate that is at least twice the frequency of the highest audio frequency component. Fig. 11a shows a sine-wave audio tone being sampled or switched on 50 percent of the time and off 50 percent of the time at a 38-kHz rate. The equation for this chopped audio waveform is

$$e = 1/2 \sin \rho t \qquad \text{audio}$$

$$+ \frac{1}{\pi} \left[\sin (\omega + \rho)t + \sin (\omega - \rho)t \right] \qquad \text{DSBSC}$$

$$- \frac{1}{3\pi} \left[\sin (3\omega + \rho)t + \sin (3\omega - \rho)t \right]$$

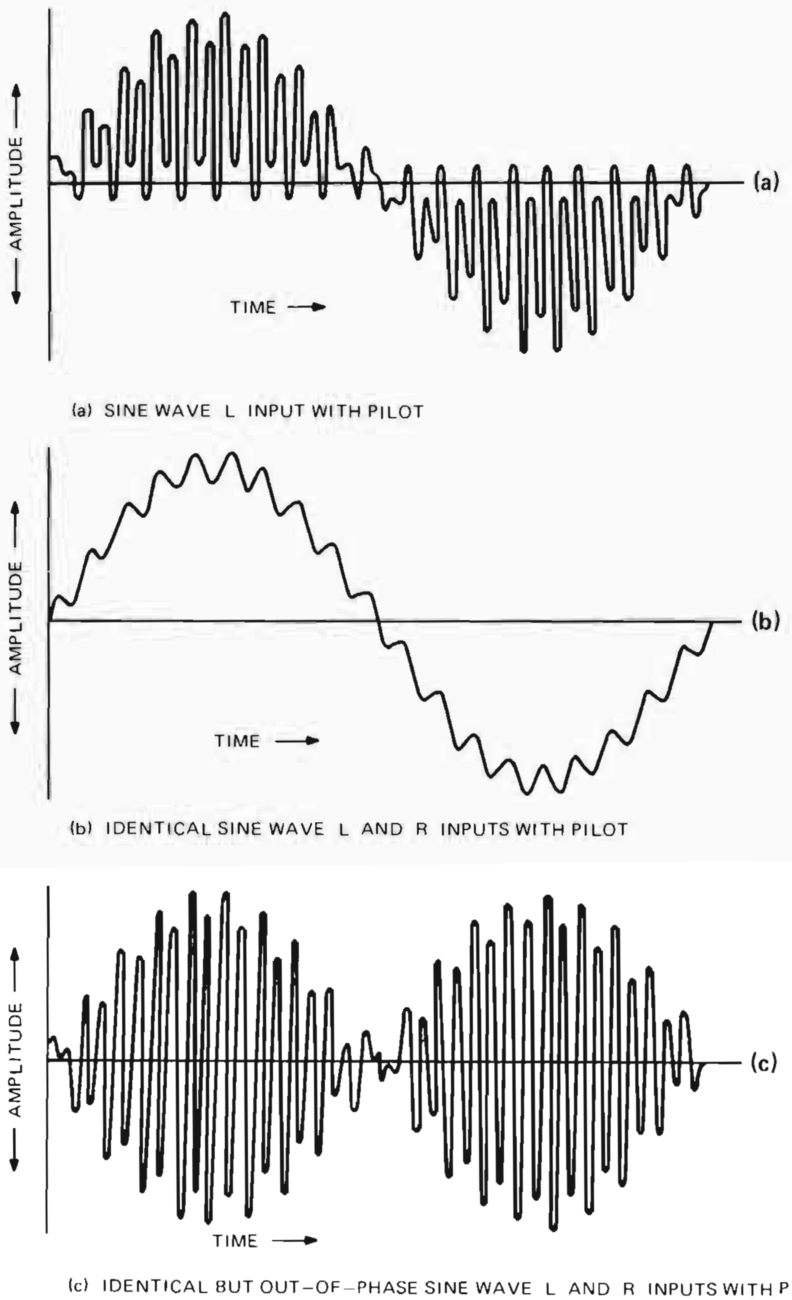


Fig. 9. Addition of pilot carrier to the same signals in Fig. 8.

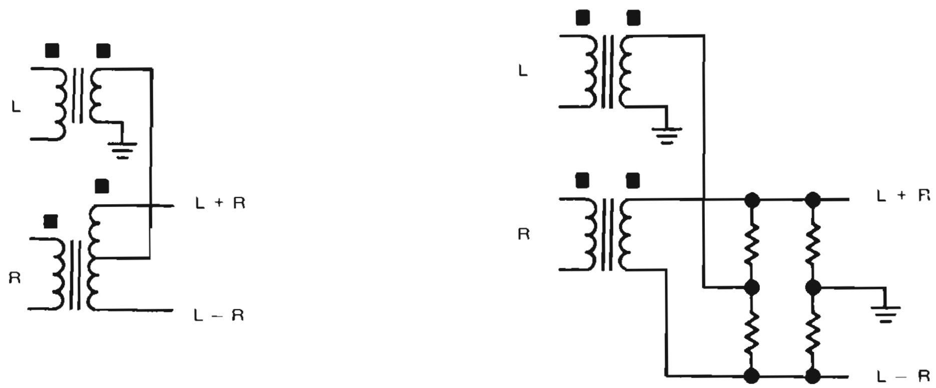


Fig. 10. Phaser addition methods to stereo matrixing.

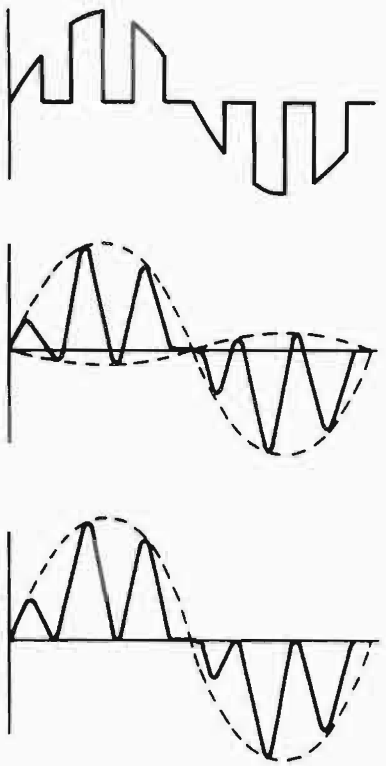


Fig. 11. (a) Output of switching type balanced modulator with sine-wave audio input and 38-kHz switching rate. (b) After removal of higher order sidebands. (c) Equal fundamental and DSBSC amplitudes.

Note that it contains the original audio at half amplitude and the double sideband suppressed carrier (DSBSC) components needed for the L-R stereo signal plus additional DSBSC terms around the 3rd, 5th, 7th, etc., harmonics of the 38 kHz switching frequency. If we filter off the third and all higher order sidebands, we get the wave shown in Fig. 11b. This is exactly the desired signal for stereophonic transmission except that the DSBSC signal is larger (when demodulated) by a factor of $\frac{4}{\pi}$. This can be overcome by simply adding enough of the input audio to the output signal to make the two equal in amplitude (Fig. 11c).

In stereo exciters that use this scheme (Figs. 31, 36, and 44) the L and R signals are sampled at alternate half cycles of the switching frequency by a double balanced modulator as shown in Fig. 12. The output contains the desired (L+R) and (L-R) DSBSC signals plus the undesired higher order products which are removed by a 53 kHz low-pass filter.

The 53 kHz low-pass filter is required to have a linear phase shift with input frequency (equal time delay at all frequencies up to 53 kHz) as well as a very flat passband amplitude response. This keeps the correct phase relationship between the L+R and L-R paths which is necessary to maintain channel separation as previously discussed.

In some exciters the 38 kHz switching frequency is obtained by dividing by two the output of a 76 kHz crystal oscillator. It is divided again to obtain the 19 kHz pilot carrier. This is simply added to the output of the 53 kHz filter to provide the desired baseband stereo signal which is used to directly frequency modulate an rf oscillator.

SCA MULTIPLEX

The FCC Rules and Regulations permit the use of frequency modulated subcarriers for subsidiary communications multiplex operation. The subcarrier frequencies are not specified, but 67 kHz is perhaps most widely used. When stereo is not broadcast, a second subcarrier at 41 kHz is often used. When broadcasting stereo, the subcarrier should not modulate the main carrier over 10 percent and when broadcasting monophonic, the sum of SCA subcarrier modulations of the main carrier should not exceed 30 percent.

The requirement that any frequency modulation of the main carrier due to SCA operation shall, in the frequency range of 50 to 15,000 Hz for monophonic or 50 to 53,000 Hz for stereophonic broadcasting, be at least 60 dB below 100 percent modulation places limits on the SCA modulation. For example, consider the case of stereo broadcasting with an SCA subcarrier at 67 kHz which is at the maximum subcarrier level of 10 percent modulation. Referring to Fig. 6, note that the subcarrier is 14 kHz above the 53 kHz edge of the stereo channel. Any SCA modulation above 14 kHz of course results in a first-order lower sideband component appearing in the stereo channel. Second- and third-order sideband components are also significant and must be kept down to an amplitude of 1 percent of the subcarrier amplitude. (Ten percent is 20 dB, which subtracted from 60 dB leaves 40 dB, which is 1 percent.) Fig. 13 shows the maximum deviation for single tone SCA modulation that complies with the Rules and Regulations. (This curve is derived from the modulation index that produces sideband components of 0.01 as found in Bessel function tables.) The lower corners of the "saw teeth" establish the limits. For example, a 4.67 kHz SCA modulating tone produces a third order sideband component at 1 percent amplitude when the SCA frequency deviation is 3.7 kHz.

Pre-emphasis of either 75 or 150 microseconds is commonly used with SCA modulation. In this case, the frequency response over the range of interest (above 3 kHz) rises at a rate of 6 dB per octave. The maximum amplitude for the SCA

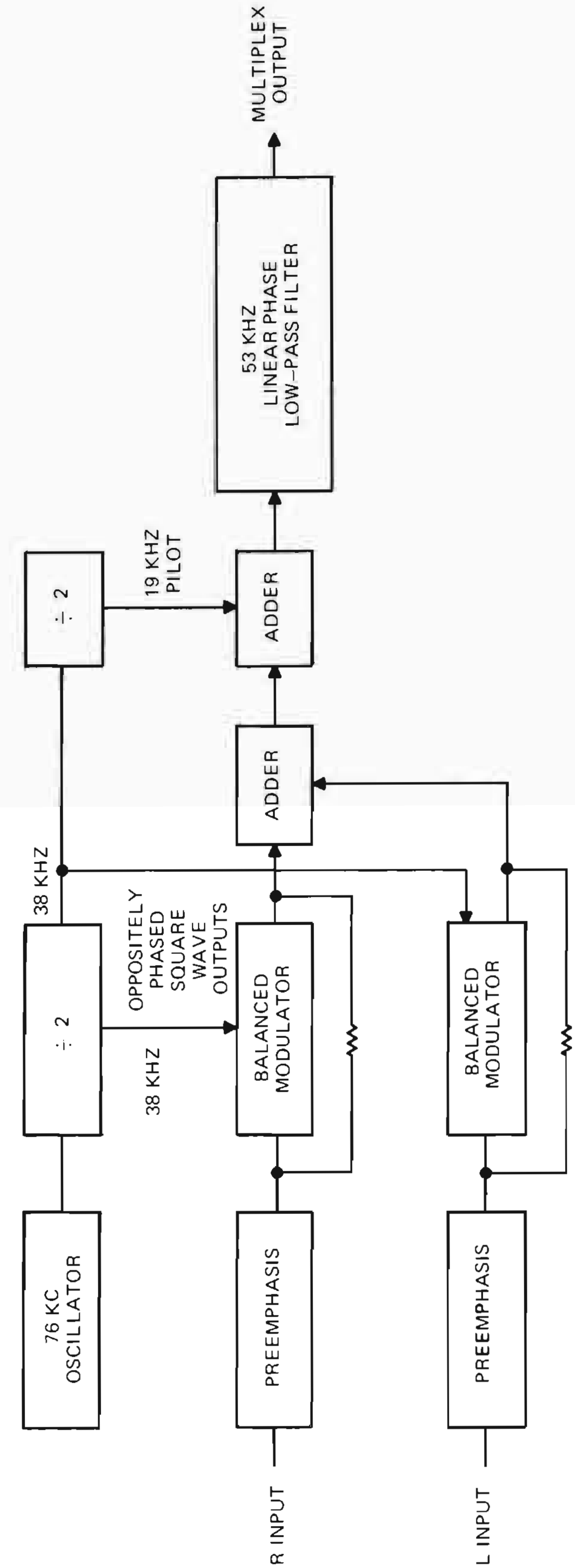


Fig. 12. Switching balanced modulator technique of stereo matrixing.

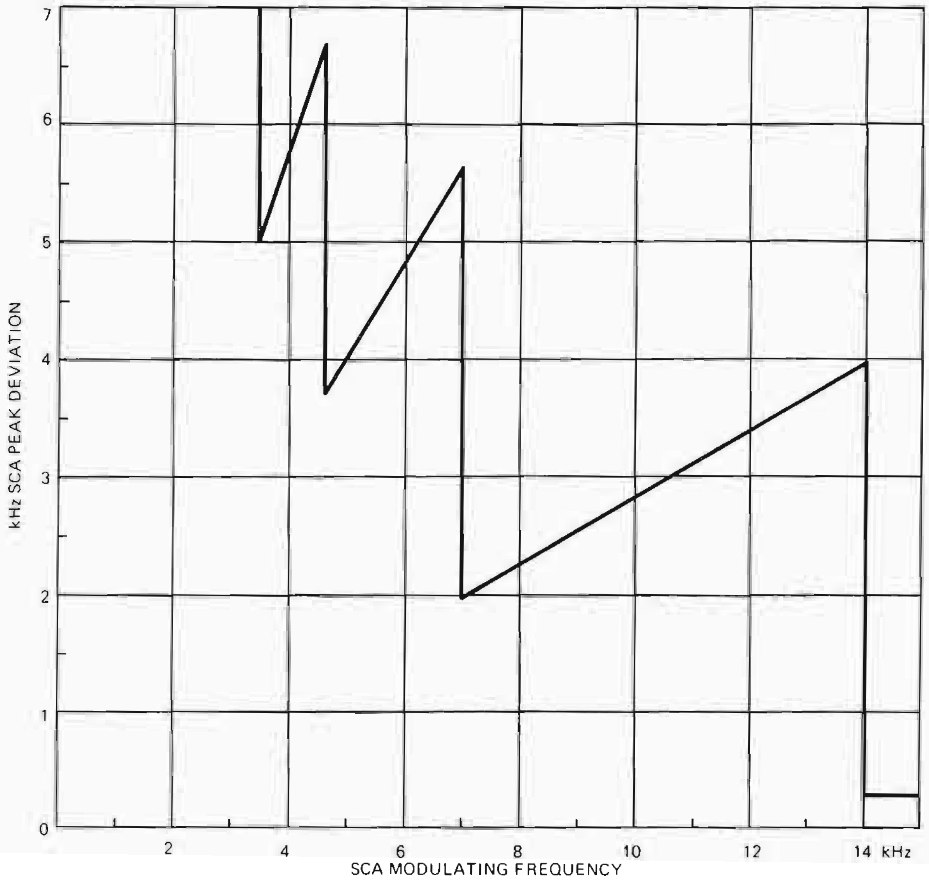


Fig. 13. Maximum deviation of 67-kHz, 10 percent amplitude SCA subcarrier with stereo broadcasting.

audio signal before being pre-emphasized is shown by the diagram in Fig. 14. This diagram indicates that frequencies above 5 kHz should be attenuated to assure compliance with the FCC regulation when program material is transmitted on the SCA channel. It is recommended practice to limit SCA modulation to 5 kHz and the peak deviation to 3.5 kHz during stereophonic broadcasts.

It is desirable to keep the SCA carrier amplitude and the frequency deviation as high as allowed in order to achieve maximum signal-to-noise ratio.

A common problem in SCA transmission is crosstalk of the main channel into the SCA channel. To minimize this condition, the exciter must have very low amplitude distortion because harmonics and intermodulation products of the main modulating signal may fall into the SCA band. The distortion must be down to the order of 0.1 percent to achieve a 40 dB S/N ratio in the SCA channel. The rf amplifiers must have very linear phase characteristics across the entire bandwidth of the transmitted signal. This requires proper tuning and neutralization. A high SWR on the antenna transmission line may also cause trouble. The receiver performance requirements are also stringent and multipath signal pickup should be minimized by using directional receiving antennas.

STEREOPHONIC SIGNAL-TO-NOISE RATIO

An important feature of the stereophonic system adopted by the FCC is that the loss in S/N to monophonic reception of a stereophonic broadcast is not great. The exact amount depends upon the nature of the signal being transmitted, but with regular program material, the loss is probably about 4 dB.

In the special case where a single test tone is fed to both L and R inputs in phase, there is no L-R signal so all of the signal appears in the main L+R channel. The level is lower by the pilot carrier amplitude which amounts to 0.7 to 0.9 dB loss.

In the case when an audio tone is applied to either the L or R input only, there is a loss of 6 dB plus 0.5 to 0.6 dB due to the pilot carrier. The

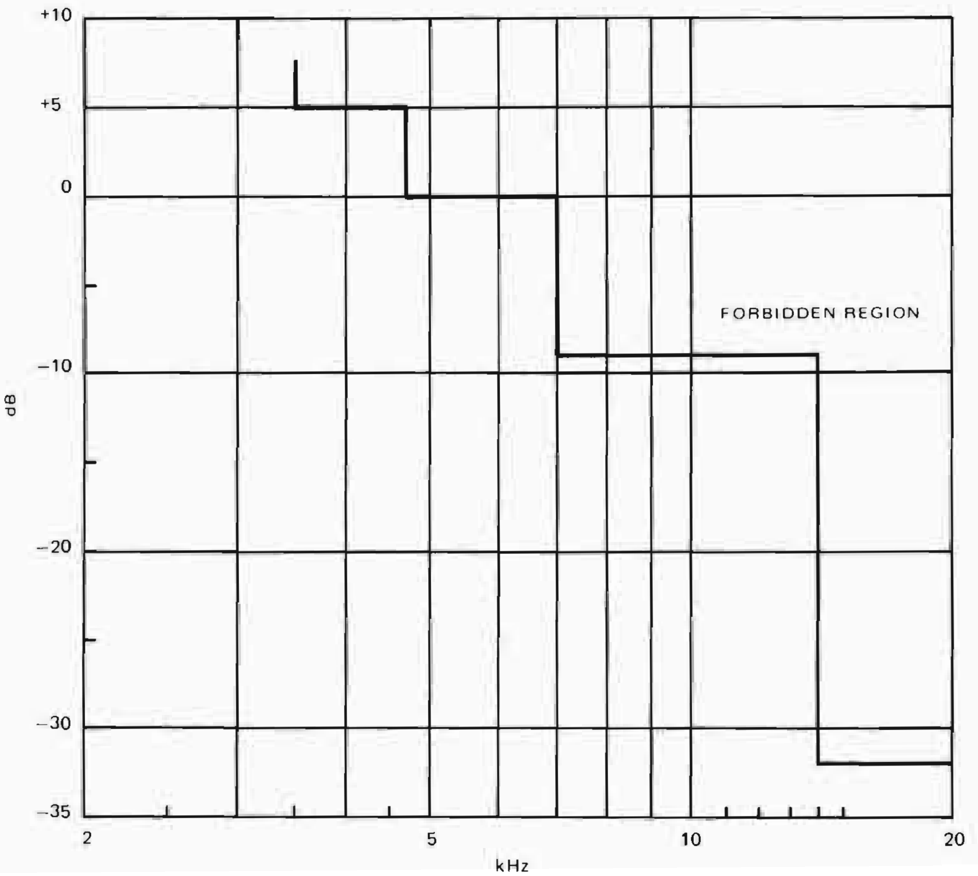


Fig. 14. Maximum frequency response of SCA modulation before pre-emphasis for a 67-kHz subcarrier frequency and stereo broadcasting on the main channel.

6 dB loss is due to the fact that the L-R component requires half the peak modulation availability. The loss for the pilot carrier is a little less because it doesn't add directly in phase with the "38 kHz" L-R component.

The loss will normally be somewhere between these two cases when broadcasting regular program material. It depends upon the extent that the L and R inputs have the same frequency components that are more in-phase than out-of-phase.

The S/N in stereophonic reception of a stereo signal is much poorer (by about 20 dB) from monophonic reception of the same signal depending on receiver audio bandwidth. The noise level in the L-R stereo channel is much greater and when combined with the L+R channel in the receiver, the noise level of the separate L and R audio channels is much greater. The reason for this is illustrated in Fig. 15. The power spectral density of noise in the discriminator output increases as the square of baseband frequency. (This assumes that the noise power spectral density is flat across the receiver bandwidth such as normally caused by receiver front end noise.) When the L-R and L+R channels are combined

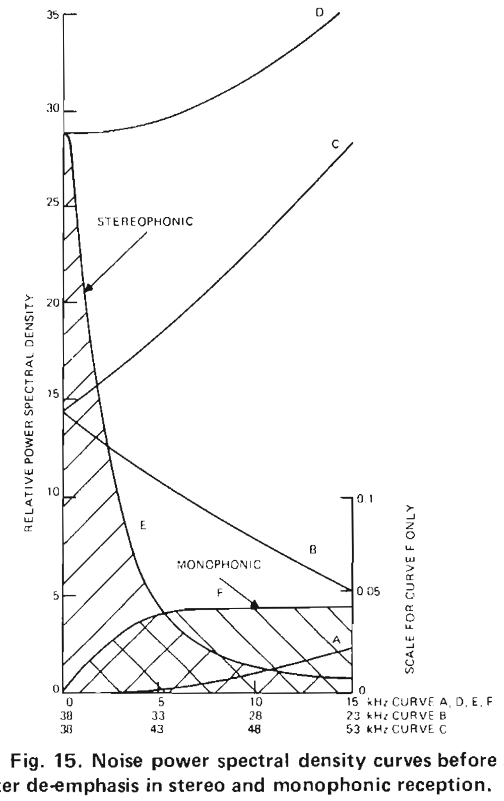


Fig. 15. Noise power spectral density curves before and after de-emphasis in stereo and monophonic reception.

in the receiver to produce the separate L and R audio channels, the noise power adds as illustrated. Deemphasis is then applied to the separate L and R audio channels resulting in the power spectral density shown for stereophonic reception. The ratio of the area under this curve to the area under the monophonic reception curve converted to decibels less 3 dB gives the difference in S/N between monophonic and stereophonic reception of the same broadcast signal. The stereophonic outputs are 2L and 2R compared to L+R monophonic output giving a 6 dB advantage due to voltage addition, with two stereophonic outputs the noise power is twice leaving the 3 dB difference.

Another factor which contributes to an improved signal-to-noise ratio is the use of automatic audio-level-controlling amplifiers and audio peak limiters. Their purpose is to keep the percentage of modulation high, which is very helpful in AM where the received S/N is normally much poorer. In FM it can be equally effective in improving received S/N and in making the station sound louder when tuning across the FM band. This improvement is not needed so much in FM broadcasting. Some program material needs the wide dynamic range afforded by FM for full effectiveness. The standards for FM broadcasting were set up to achieve good high fidelity capability so good judgment should be exercised in the amount of audio compression and peak limiting used.

AUTOMATIC FREQUENCY CONTROL

The frequency stability of direct FM oscillators is not good enough to meet the FCC frequency tolerance limit of 2,000 Hz. This requires an automatic frequency control system of some kind that uses a stable crystal oscillator as the reference frequency. Several different schemes are employed by the various manufacturers.

The modulated oscillator should have good long-term stability (within practical limits) to avoid the need of excessive control loop gain. It also needs good short term stability (that is, < 1 second) because the control loop time constant must be long enough that the AFC circuit does not try to remove desired low-frequency audio modulation. The audio frequencies are usually attenuated below 20 Hz so they will not interfere with the AFC operation.

There are three basically different AFC schemes currently in use. One scheme is shown in Figs. 31 and 45. The modulated oscillator output frequency is divided by 2^{14} (which is 16,384) to obtain a frequency in the 6-kHz region. A crystal oscillator operating on 2^{-10} or 1/1024 of carrier frequency is divided by 24 or 16 to arrive at the same frequency. The two frequencies are compared in a phase detector to develop an output voltage for controlling the carrier frequency of the modulated oscillator. The reason for dividing the modulated oscillator frequency so far down is to lower the modulation index sufficiently to avoid carrier disappearance and remove most of the modulation. A 50 Hz audio input producing 100 percent modulation of a carrier divided this much results in a modulation index of only 0.0916. The phase detector output is filtered to further remove all frequency components above a few Hz so that the AFC circuit does not try to remove low-audio frequency modulation.

Figs. 39 and 50 illustrate an AFC scheme where the modulated oscillator frequency is converted downward to a 200 or 400 kHz region. The signal at this if. frequency still contains the full ±75-kHz modulation and there are sideband frequencies extending beyond that. This FM if. signal wave is shaped into pulses and a counter type detector is used to produce the error correcting signal. Again enough integration time or low pass filtering must be used to minimize response to low audio frequencies.

The other scheme is used in the exciter shown in Fig. 36. The 14 MHz modulated oscillator output is compared with a 14 MHz reference crystal oscillator. This is accomplished by alternately sampling one and then the other at approximately a 5 Hz rate using a synchronous switching scheme and a discriminator for the detector. Errors due to discriminator drift and AFC amplifier dc drift are thereby eliminated. The modulation in the discriminator output during the periods when the modulated oscillator is being sampled is cancelled by feeding the original baseband modulating signal into the discriminator output out of phase. The remaining signal is filtered and the ±dc component is used to keep the oscillator on frequency.

FM EXCITERS

The function of the exciter is to generate and modulate the carrier wave with the one or more inputs (mono, stereo, SCA) in accordance with the FCC standards. Stereo transmission places the most stringent performance requirements upon the exciter. Most, if not all, exciters now being manufactured are designed to meet the FCC stereo requirements. They are modulized or unitized so they can be procured for just mono or mono plus SCA transmission. Later conversion to stereo can be accomplished simply by adding the necessary modules or units.

Before the advent of stereo broadcasting, most of the FM exciters employed phase modulation techniques. Some of these were adapted to stereo but it was difficult to achieve and maintain the performance standards for stereo separation. All manufacturers now employ direct FM systems. Each manufacturer has a different variation but they all have the same basic requirements and characteristics.

All exciters being manufactured will produce at least 10 watts output so they can also be used as the transmitter for the 10 watt educational stations. For higher power outputs, the exciter is used to drive a power amplifier.

TRANSMITTER POWER OUTPUT REQUIREMENT

The FCC regulates the power of FM broadcast stations in terms of effective radiated power (ERP). The ERP authorized applies to the horizontally polarized component of radiation. Elliptical or circular polarization is also permitted, in which case the ERP of the vertically polarized component may be as great as the authorized horizontal component. This means that twice as much actual power may be radiated.

The transmitter power required can be reduced by increasing the gain of the antenna. There is, of course, an economic tradeoff between the cost of a higher gain antenna versus the cost of a larger transmitter and the added primary power costs. For the higher ERPs, it is common to use antennas with up to 12 elements which provide a power gain of about 12.5 (or 6.3 in each polarization).

The long transmission lines associated with the tall towers commonly used are a source of considerable power loss. For example, the efficiency of 2000 ft. of 3-1/8 in. coax is 62.5 percent.

FM transmitters are designed to operate over a range of power outputs so that with a few basic sizes any required power output can be furnished. Popular maximum ratings range from 250 watts to 40 kilowatts. Forty kilowatts is a practical maximum because that is about all a 3-1/8-in. coaxial transmission line will carry and because it is more economical to achieve the maximum of 100-kilowatts ERP with circular polarization by means of sufficient antenna gain.

The authorized power for educational stations is 10 watts. Most exciters are designed with a power output of 10 watts so they can be used as the complete transmitter for educational stations with the addition of an rf harmonic output filter.

RF POWER AMPLIFIER PERFORMANCE REQUIREMENTS

The basic function of the power amplifier is to amplify the power of the exciter output to the authorized transmitter power output level. Most of the overall transmitter performance characteristics are determined by the exciter but a few are established or affected by the power amplifier characteristics.

1. The output at harmonics of the carrier frequency is almost completely a function of the attenuation provided by the output tank circuit and output filters. The limit in decibels is 43 +10 $\log_{10}$ power or 80 dB whichever is less. (This is 73 dB for 1 kw output and 80 dB for 5 kw and higher.)

2. The major source of AM noise usually originates in the last power amplifier stage. The FCC limit is 50 dB below 100 percent modulation.

3. The rf power output control which must keep the output within +5 percent and -10 percent of authorized output is achieved in the final power amplifier.

4. Inadequate bandwidth particularly with respect to phase linearity across the signal bandwidth can reduce stereo separation and cause SCA crosstalk.

Note: The presence of standing waves on the transmission line to the antenna may also react on the power amplifier to cause degraded stereo separation and SCA crosstalk.

The power amplifiers should provide trouble-free service and be easy to maintain and repair. Good overall efficiency is also desirable to keep down the primary power consumption.

POWER AMPLIFIER CIRCUITS

The amplitude of an FM signal remains constant with modulation so that efficient Class B and C amplifiers can be used. Most exciters being manufactured at this writing use transistors to generate the 10 to 20 watts of output power. It is technically feasible to develop transistor amplifiers for any required higher power but they are not yet economically competitive. A great deal of circuitry is involved because it takes the combined output of a great many transistors to produce a few kilowatts of power output. For this reason, the following discussion will relate to vacuum tube amplifier circuits.

FM broadcast power amplifier circuits have evolved to two basic types. One uses tetrode or pentode tubes in a grid driven circuit and the other uses high mu zero bias triodes in cathode driven (grounded grid) circuits.

CATHODE-DRIVEN TRIODE AMPLIFIERS

The high-mu triodes being used in FM amplifiers were originally developed for linear SSB amplifiers. Their characteristics are well adapted to FM broadcast use because the circuit is very simple and no screen or grid bias power supplies are required. Fig. 16 shows one basic circuit configuration. In this case, the grid is connected directly to chassis ground. Dc grid current is the

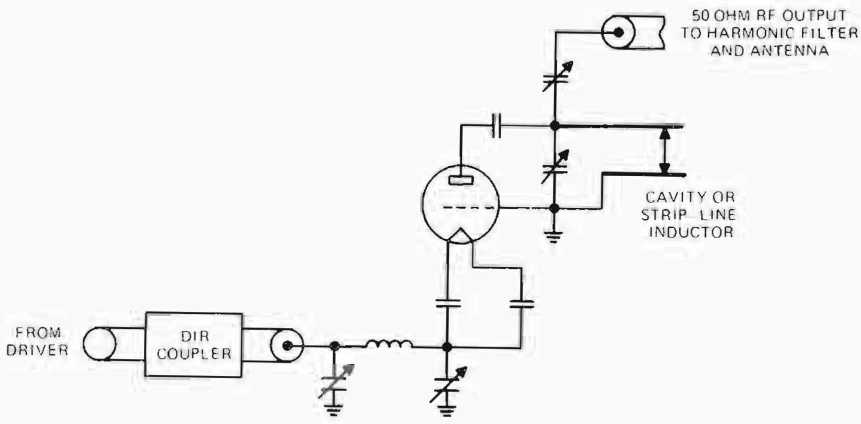


Fig. 16. Cathode-driven triode power amplifier.

difference between dc cathode current and dc plate current. The output tank circuit is a shorted coaxial cavity which is capacitance loaded by the tube output and stray circuit capacitance. A small capacitor is used for trimming the tuning and another small variable capacitor is used for adjusting the loading. A pi-network matches the 50 ohm input to the tube cathode.

These triodes are usually operated in the Class B mode in order to achieve maximum power gain, which is on the order of 20. They could be driven into Class C operation by providing for grid bias. This would increase plate efficiency but at the expense of increased drive power.

Most of the drive power is fed through the tube and appears in the stage output. This increases the apparent efficiency so that the efficiency factor given by the manufacture in conformance to the FCC regulations may be higher than the actual plate efficiency of the tube. For example, assume 10,000 watts of rf power output of which 500 watts was fed through with an assumed plate efficiency of 70 percent for the 9,500 watts generated by the final stage, the final dc plate input is 13.57 kw; the apparent efficiency of $\frac{10.00\ \text{kw}}{13.57\ \text{kw}}$ or 73.7 percent, which would be the legal efficiency factor.

Since most of the drive power is fed through the tube, any changes in loading of the output circuit will affect the operation of the input tuning and driver operation.

There is rf drive voltage on the cathodes (filaments) of cathode driven tubes, so some means must be used to keep it out of the filament transformer. One method employs rf chokes since the inductance can be very low. The other commonly used method feeds the filament power up through the input tank circuit inductor.

Apparently none of the cathode driven amplifiers being marketed require neutralization. The high-mu triodes being used have an advantage of about one order of magnitude regarding the need for neutralization.

It is necessary that the grid-to-ground inductance both internal and external to the tube be kept very low to maintain this advantage, however. Omission of neutralization, of course, will allow a small amount of reaction of the output circuit upon the input circuit through the plate-to-filament capacitance path, but it is not noticeable because of the large coupling between the input and output circuits through the electron stream of the tube.

Cathode driven stages are normally used only for the higher power stages. The first stage in a transmitter is nearly always a tetrode because of its higher power gain.

GRID-DRIVEN TETRODE AND PENTODE AMPLIFIERS

A small tetrode tube such as the 4CX250B or 8122 is commonly used as the only amplifier stage in 250 watt transmitters and in the driver for higher power stages. The largest one-tube transmitter available at this writing uses a 5CX1500A to deliver 2 kw. Higher power outputs require two stages.

Transmitters using tetrode amplifiers throughout usually have one less stage than those using triodes. Since tetrodes have very high power gain, they are driven into Class C operation for higher plate efficiency. Against these advantages is the requirement for screen and bias power supplies.

Fig. 17 shows a schematic of a grid-driven tetrode amplifier. In this example, the screen is operated at dc ground potential and the cathode (filament) is operated below ground by the amount of screen voltage required. This is called grounded-screen operation. It has the advantage that stability problems due to undesired reson-

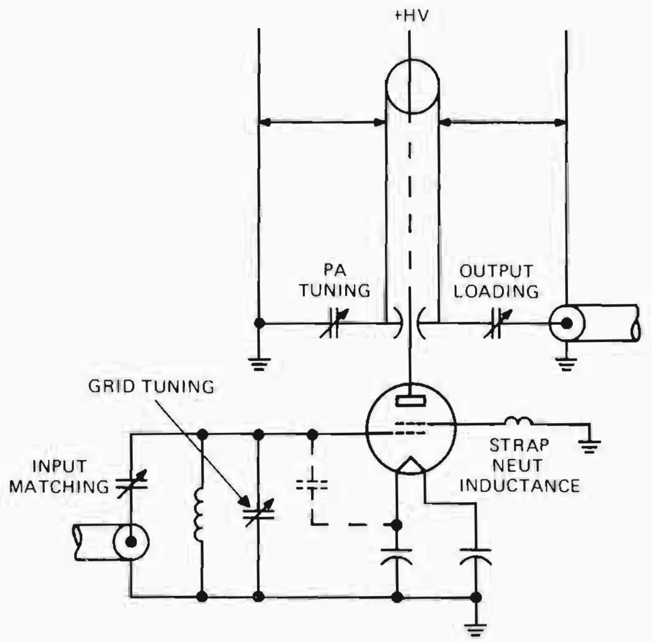


Fig. 17. Grid-driven grounded screen tetrode power amplifiers.

ances in the screen bypassing capacitors are eliminated. With filament type tubes, it is necessary to use filament bypass capacitors anyway; although with grounded-screen operation, they have the dc screen voltage across them. Coaxial cavity input and output circuits are shown. The circulating current is spread over large surfaces so the losses are very low. These cavities are basically shorted transmission line sections which resonate the tube input and output capacitances. Their lengths are preset to the desired carrier frequency and then small variable capacitors are used to trim them into resonance. Capacitive coupling to the 50 ohm output is used for mechanical convenience. The 50 ohm input is tapped onto the grid circuit inductor to provide the correct impedance match.

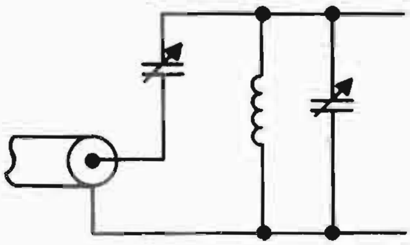
The grid circuit is usually loaded with added resistance. The purpose is to broaden the bandwidth of the circuit by lowering the circuit Q and to provide a more constant load to the driver. It also makes neutralizing less critical so that the amplifier won't become unstable and oscillate even with the output circuit completely unloaded.

Cathode or filament lead inductance from inside the tube, through the socket and filament capacitors to ground, can heavily load the input circuit. This is caused by rf current flowing from grid to filament through the tube capacitance and then through the filament lead inductance to ground. This produces an rf voltage on the filament which in effect causes the tube to be partly cathode driven. This undesired extra drive power can be minimized by series resonating this path by proper choice of filament bypass capacitors.

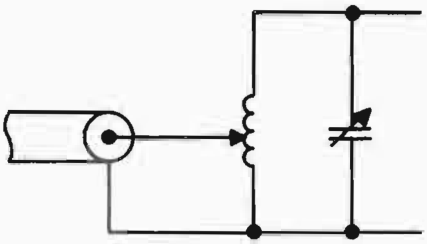
The larger high gain tetrodes need accurate neutralization for best stability and performance. This is accomplished very simply by placing a small amount of inductance between the tube screen and ground. This inductance is usually in the form of several short adjustable length straps. The principle involved is that the rf current flowing from plate to screen in the tube also flows through this screen lead inductance. This results in a small voltage on the screen of the opposite phase which capacitively couples to the control grid just enough to neutralize the small amount of plate to grid capacitance present.

INTERSTAGE COUPLING CIRCUITS

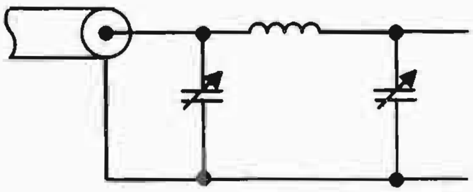
Separate driver plate and final grid rf circuits are commonly used and coupled together by a coaxial transmission line. Impedance matching is usually accomplished by one of the means shown in Figs. 18a, 18b, and 18c. In order to keep from having excessive current in the interconnecting transmission line the coupling circuits must be matched to the transmission line impedance. Directional wattmeters are normally placed in the line to measure forward and reflected power from which standing wave ratio can be established. The SWR is established entirely by the match at the load end of the transmission line. At the input end of the line the driver plate output circuit matches the transmission line load to the desired load on the driver tube.



(a)



(b)



(c)

Fig. 18. Interstage rf coupling circuits.

This transmission line matching problem is eliminated in some transmitters by locating the driver tube close to the final tube so that simple coupled circuits can be used. This eliminates the need to go through the intermediate impedance of a transmission line.

OUTPUT COUPLING CIRCUITS

Usually the output circuit consists basically of just a high-Q cavity, strip line, or inductor to resonate the tube output capacitance. To this is added a means of trimming the tuning and a means of adjustable coupling to the output transmission line. The tank circuit loaded Q is kept as low as practical to minimize circuit loss and, also, to keep as wide an rf bandwidth as practical.

The plate tank circuit does not provide enough harmonic attenuation to meet FCC regulations, a harmonic filter is used for this purpose. The FM band is narrow enough that one low pass filter design can be used for any carrier frequency. The filters for low power transmitters may employ lumped elements (coils and capacitors), but filters for high power employ distributed element or transmission line techniques. The art of filter design is very highly developed and this technology is well documented in the microwave literature.

Design theory will not be covered here but it is pointed out that when two filters (such as the output cavity and the harmonic filter) are connected together by a transmission line, the total harmonic attenuation realized will vary with interconnecting line length.[4] The attenuation of separate harmonic filters is specified for the case where the source impedance and load impedance are equal to the transmission line impedance the filter was designed for. Test instruments provide this situation. In actual use, however, the source and load impedances are nowhere near 50 ohms and tend to lie near the outside edge of a Smith chart. If an unfortunate length of line is selected, it can be corrected by changing the line length 2 feet or so. When the filter is designed into the transmitter cabinet, the line length between the tank circuit and harmonic filter is fixed at a value known to be satisfactory by the transmitter manufacturer.

HYBRID COMBINING TWO RF AMPLIFIERS

It has become quite popular at the 20 kw and 40 kw power level to combine the output of two power amplifiers. The important advantage is that the broadcast transmission is not interrupted when one amplifier fails. The radiated signal strength merely drops 6 dB until the failed amplifier is repaired and put back on the air. A dual amplifier costs more than a single amplifier for a given total power output, but there are the economic advantages of reducing lost air time and eliminating the need for a separate standby transmitter. Some stations go one step further and install dual exciters also so that if one exciter fails, the other one can be quickly switched into service.

Fig. 19 shows a block diagram of a pair of combined amplifiers and dual exciters. (The exciters cannot be operated in parallel like the amplifiers because their rf outputs would have to be on exactly the same carrier frequency and almost exactly in phase under all modulation conditions.) The exciter in use feeds a power splitter which transforms one 50 ohm input into two 50 ohm outputs with half power going to each. The exciter must have enough power output capability to drive both power amplifiers, of course. The length of coax from the power splitter to the amplifier inputs must be exactly the same

[4] There is a class of filters called absorptive filters which are independent of the source impedance of harmonic energy.

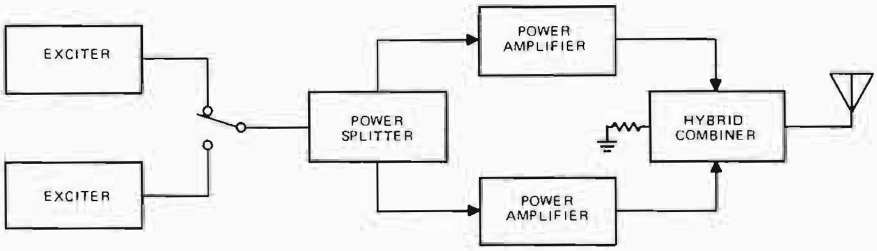


Fig. 19. Block diagram of transmitter with two power amplifiers, a hybrid combiner and dual exciters.

length so that the amplifiers will be fed in phase. The amplifier inputs should properly terminate the input coax in all conditions even when the amplifier is turned off.

The output hybrid combiner effectively isolates the two amplifiers from each other. Tuning adjustments can be made on one amplifier including turning it on and off without appreciably affecting the operation of the other amplifier. The degree of isolation achieved depends mostly upon the SWR on the transmission line to the antenna. Good isolation is necessary so that when one transmitter fails, the other will continue to operate normally instead of in a mistuned condition. This really does not place an added burden on the antenna system because it is desirable to keep the SWR down to 1.1 to 1 to maintain good stereo separation and low SCA crosstalk anyway.

Hybrid combiners are basically 4-port devices. Two of the ports are the two 50 ohm inputs, the sum port is the 50 ohm antenna output terminal, and the difference port goes to a dummy load. When the power fed to each of the two inputs is equal and in phase, the total power is delivered to the sum port (antenna). This holds true even if there are standing waves on the antenna coax. The input ports will present a load to the transmitters with the same SWR as on the antenna coax. If, however, the two inputs from the separate amplifiers are not equal in amplitude or exactly in phase, there will be some power dissipated in the difference port dummy load. The match in input power and phase is not at all critical as shown in Fig. 20, and the power lost in the difference port load can be easily reduced to a negligible value by touching up the amplifier tuning.

When one transmitter fails, the result is that half of the working amplifier output goes to the antenna and the other half is dissipated in the difference port load. This is why the radiated output drops to one-fourth power or by the 6 dB mentioned earlier.

For perfect amplifier isolation, the load impedance on the sum and difference ports must be exactly the same. This is approached in practice by providing a 1.0 to 1 SWR termination on the difference port and then getting the SWR on the antenna feed coax as low as possible by means of trimming the antenna match. This keeps the input port impedances from changing too much when one amplifier fails or is off for any reason.

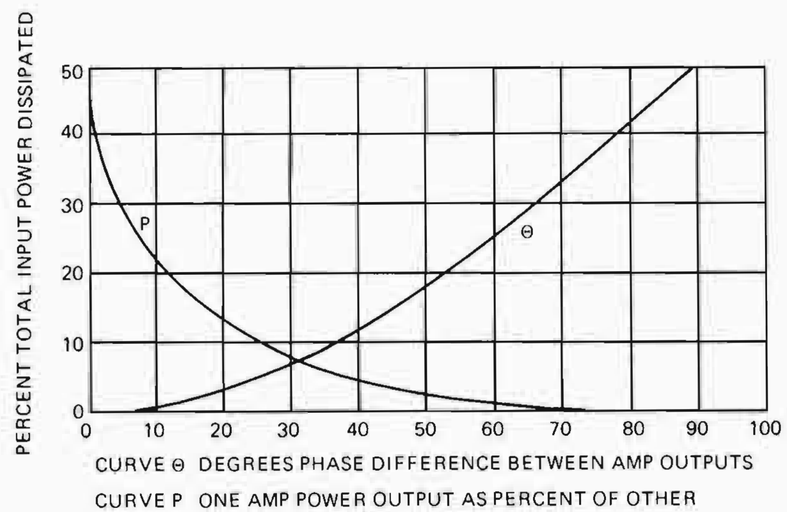


Fig. 20. Power loss in hybrid due to amplitude or phase difference in power amplifier output for the case of 1.0 to 1 antenna transmission line SWR.

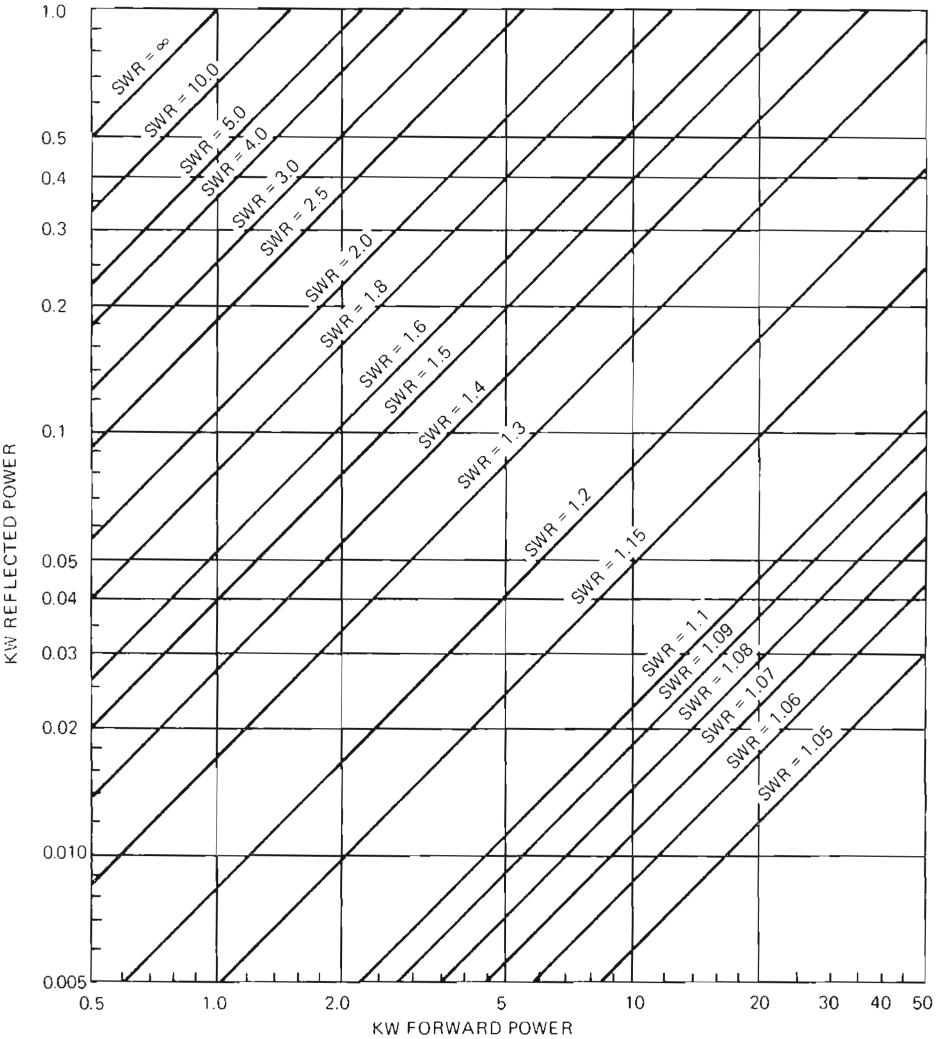


Fig. 21. Chart of SWR versus forward and reflected power.

DIRECTIONAL WATTMETERS

Directional wattmeters are instruments that measure the forward P_F and reflected P_R power in a transmission line. The net power delivered to the load (antenna) is $P_F - P_R$. The standing wave ratio (SWR) on the transmission line can be computed with the following formula.

$$SWR = \frac{1 + \sqrt{\frac{P_R}{P_F}}}{1 - \sqrt{\frac{P_R}{P_F}}}$$

This relationship is shown graphically in Fig. 21 so the SWR can be obtained without computation.[5]

[5]W. B. Bruene, "An Inside Picture of Directional Wattmeters," April 1959, QST.
Bird Electronic Corporation Catalog.

The standing wave is due to the presence of two components of power, one traveling toward the load and the other, having been reflected by the load mismatch, traveling back toward the generator.

$$P_F = \frac{E_F^2}{Z_o} = I_F^2 Z_o$$

$$P_R = \frac{E_{F_R}^2}{Z_o} = I_F^2 Z_o$$

$$P = P_F - P_R$$

The subscripts F and R are used to denote forward and reflected and Z_o is the characteristic impedance of the transmission line. P is the net power absorbed by the load (transmission line loss and antenna radiation).

Since the forward and reflected voltage and currents are traveling in opposite directions, they

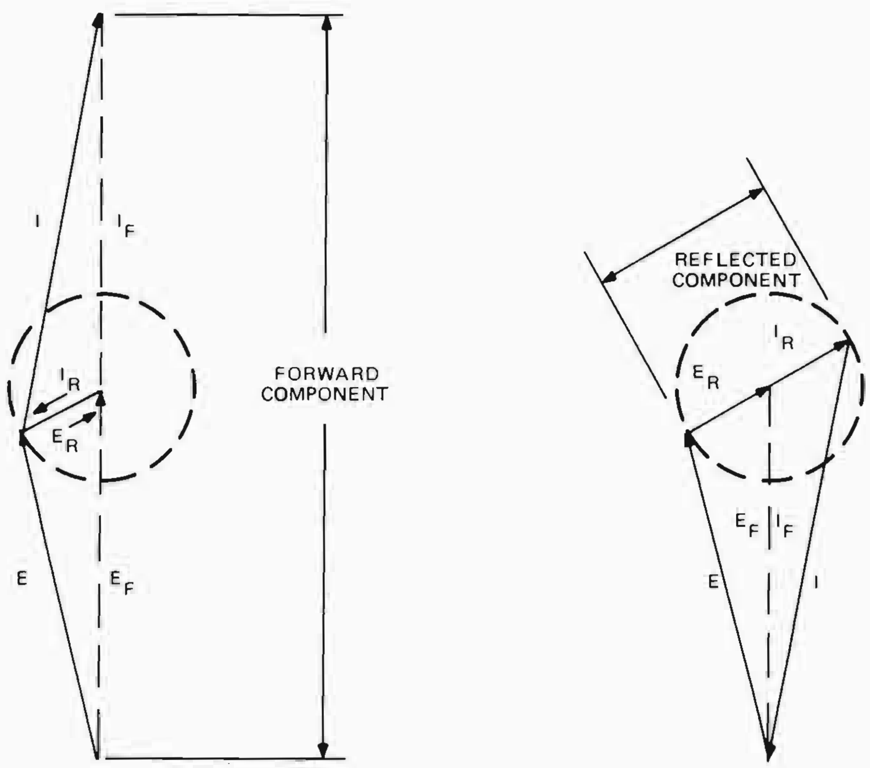


Fig. 22. Phasor addition of voltage and current samples to separate forward and reflected components.

will add in phase at some point along a line of sufficient length to produce a voltage maximum. One-quarter wave length along the line in either direction the forward and reflected components are out of phase and produce a voltage minimum. The forward and reflected components of current, also, add to produce a current standing wave. The magnitude of the standing wave is defined as:

$$SWR \doteq \frac{E_{max}}{E_{min}} = \frac{I_{max}}{I_{min}}.$$

At the point of reflection (for example, the load mismatch), the phase of the reflected current is reversed 180° from the forward current. The reflected voltage does not have this phase reversal. This displaces the voltage and current standing waves by 90° along the line so that the E_{max} and I_{min} occur at the same points and E_{min} and I_{max} 90° away.

The fact that the reflected current is reversed in phase makes it possible to measure forward and reflected power separately. A small voltage is obtained (usually by inductive coupling) which represents the current in the transmission line. To this is added a sample of the voltage across the line. The samples are adjusted to be exactly equal when the line is terminated with its characteristic impedance (that is, no standing waves and, hence, no reflected components). These two rf samples are added, which gives an rf voltage proportional to the forward components of voltage and current as illustrated in Fig. 22. The forward components of the samples are equal and in phase but the reflected components of voltage and current balance out. By reversing the phase of the current sample, the reflected components add while the forward components balance out. These voltages representing the forward or reflected voltage and current are usually rectified to feed a meter. The meter scale is calibrated to read the square of its input so that P_F of P_R are read out directly.

The SWR on an FM antenna transmission line must be kept down to the order of 1.1 to 1 for good stereo performance. It takes very little reflected power to produce substantial SWR as shown in Fig. 23. For this reason the reflected power is usually read on a more sensitive meter position. Troubles in the antenna system such as loose connections or icing may cause excessive SWR. Instruments[6] are available that monitor reflected power and energize an alarm if it becomes excessive. As long as the transmitter power output is fairly constant, the use of reflected power to indicate excessive SWR is simple and adequate.

[6]Watcher RF Power Monitor/Alarm, Bird Electronic Corporation.

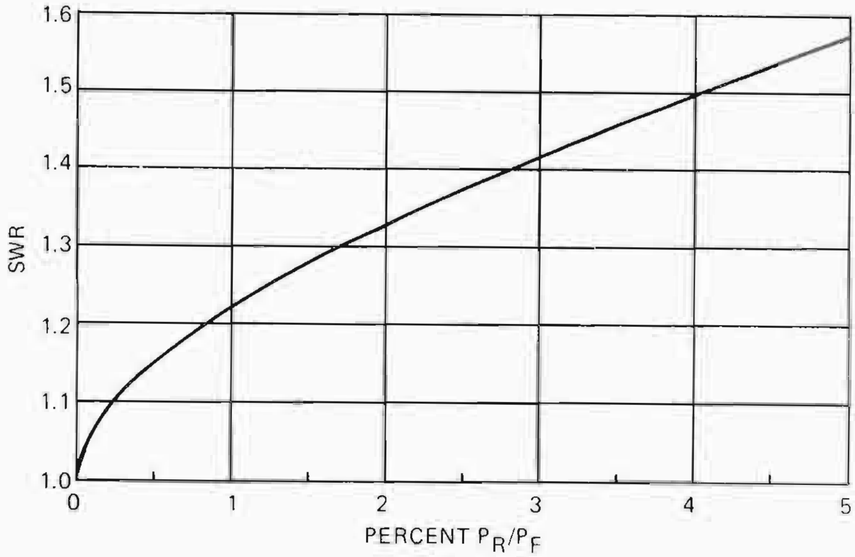


Fig. 23. Relationship of SWR to ratio of reflected power to forward power.

TRANSMITTER DESCRIPTIONS

Brief descriptions and photographs of several FM broadcast transmitters are shown to show the general appearance of the equipment and the basic circuits employed. The basic circuits and principles have been discussed in a general way in previous discussion. Since the FCC requires type approval, it can be expected that all satisfy FCC requirements. No attempt will be made to compare equipment specifications or to evaluate the features offered by the various manufacturers. The reader is cautioned that the transmitters and exciters described in this section may be superseded by newer models at any time. The manufacturers should be contacted directly for more complete information on their latest models.

Figs. 24 and 25 are photographs of the AEL FM-3KB 3-kw transmitter and Model 2202 FM exciter manufactured by American Electronic Laboratories, Inc. Fig. 26 shows block diagrams of the exciter and the Model 2203 Stereo Generator. The exciter uses direct FM of an oscillator operating on carrier frequency. They also manufacture a solid state SCA Generator Model 2204. AEL manufactures seven transmitter models which are rated to cover all power output levels from 250 watts to 40 kw. Some use tetrode and others use zero bias triode final amplifiers. Representative block diagrams are shown in Fig. 27 and Fig. 28.

Fig. 29 is a photograph of Bauer Model 603 3 & 5 kw FM Broadcast Transmitter with the front door open and Fig. 30 shows a view of the Model 660 FM Exciter manufactured by Bauer Communication Products Division of Granger Associates. Fig. 31 shows block diagrams of the FM exciter and of the stereo generator. The exciter

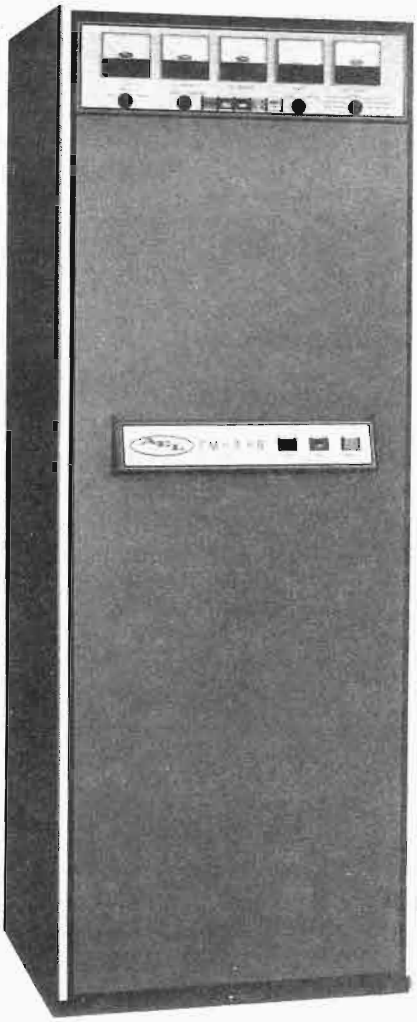


Fig. 24. American Electronic Laboratories Model FM-3KB 3-kw Transmitter.

Fig. 25. American Electronic Laboratories Model 2202 FM Exciter.

consists of a power supply which is built into the chassis plus three to five modules; the standard rf amplifier and exciter modules, a choice of monaural or stereo generator and two optional SCA generators. Direct FM is used with the oscillator operating at carrier frequency. The reference crystal oscillator operates at 2^{-10} or $\frac{1}{1024}$ of the carrier frequency. The FM oscillator and crystal oscillator frequencies divide down to a common

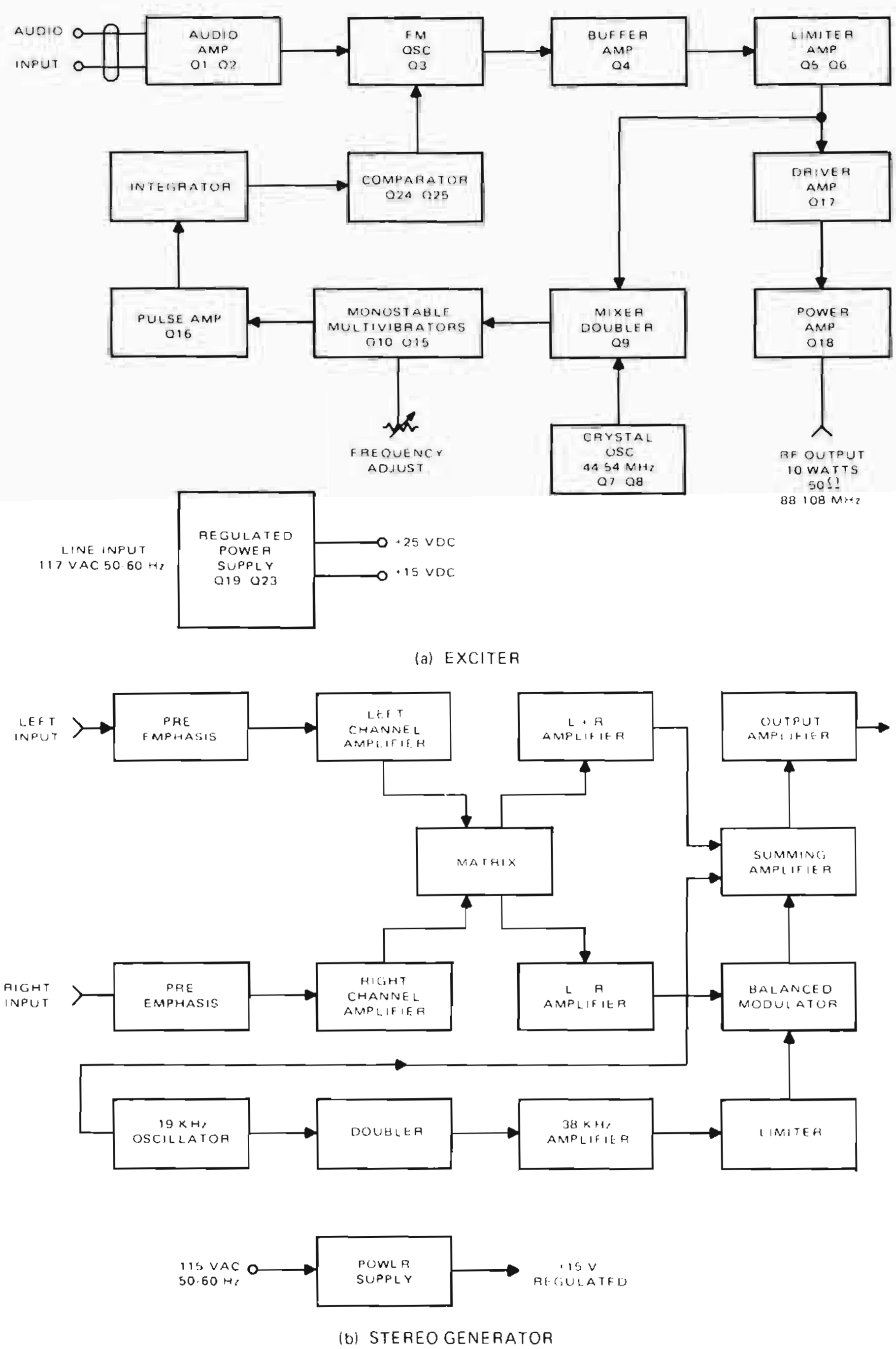


Fig. 26. Block diagrams of AEL Model 2202 Exciter and Model 2203 Stereo Generator.

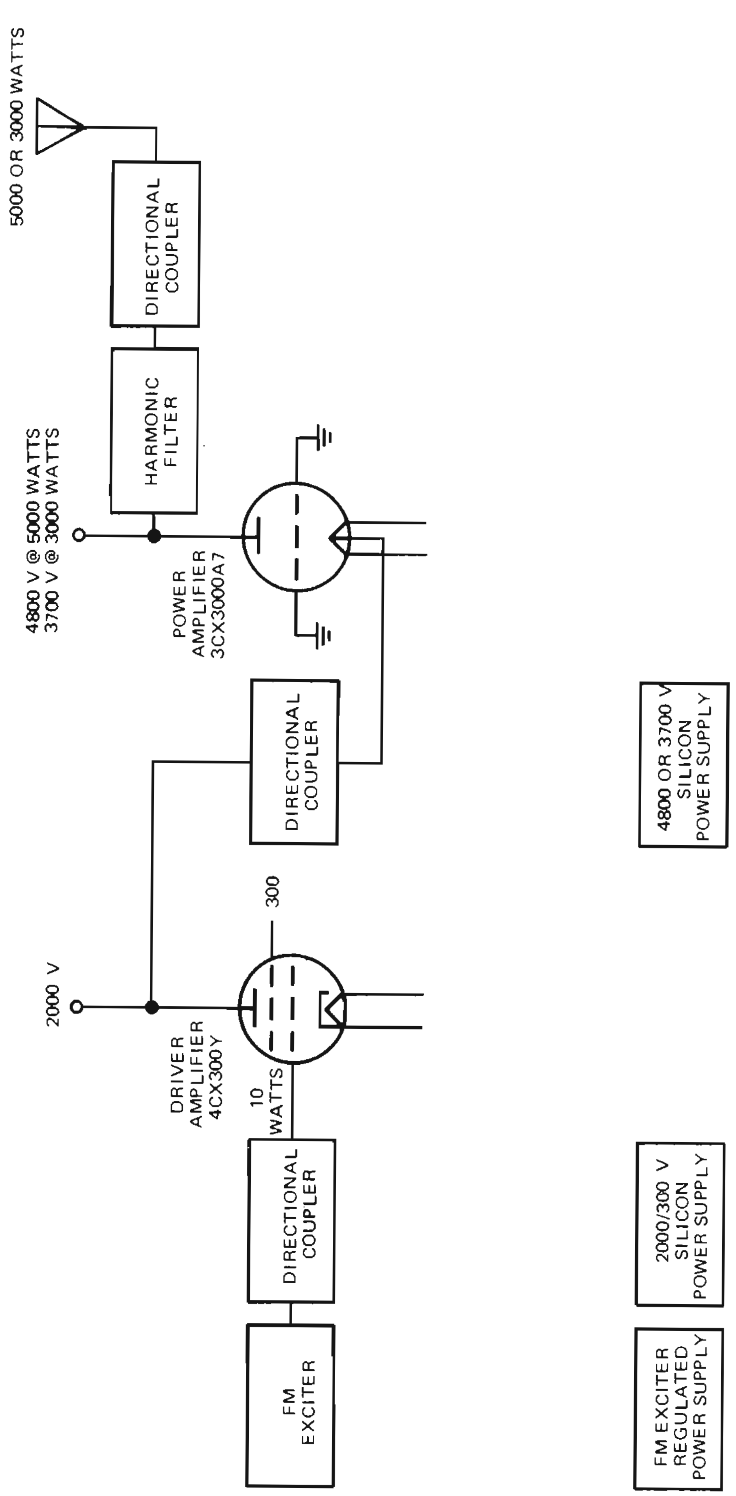


Fig. 27. Block diagram of AEL 3-kw and 5-kw transmitter.

frequency in the 5.4 to 6.6 kHz range for phase comparison and AFC control. The stereo generator uses the 38-kHz switching method of stereo signal generation.

The photograph in Fig. 32 shows the appearance of CCA 5, 10, and 20 kw transmitters manufactured by CCA Electronics Corporation. They also manufacture transmitters for the 10 watt, 250 watt, 1 kw, and 3 kw power levels. The CCA employs high-mu zero bias triodes in the final amplifier of all transmitters from 1 kw to 20 kw. A single tetrode tube provides the gain

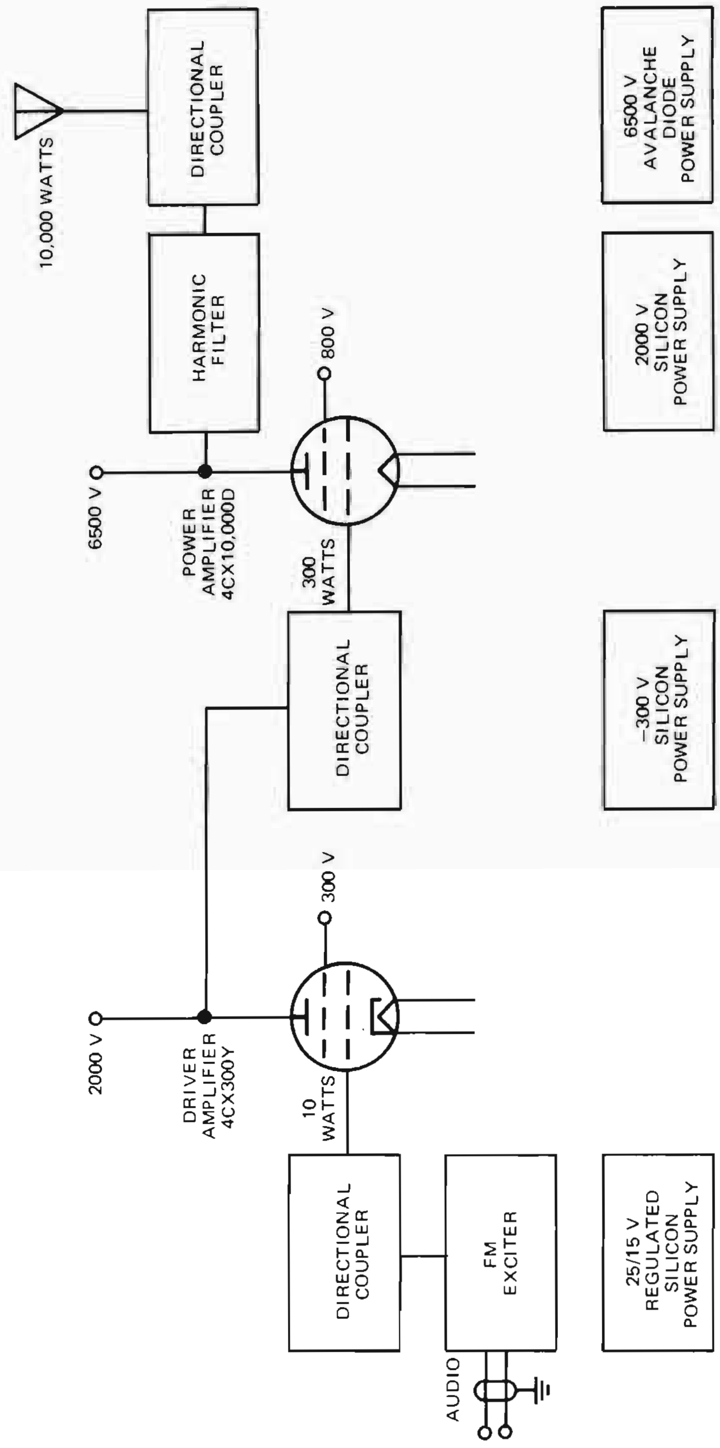


Fig. 28. Block diagram of AEL 10-kw transmitter.

necessary to drive the triode final amplifier stage in all but the 20 kw transmitter where two tetrode stages are employed. The CCA transmitters are available with either of two models of exciters. One employs phase modulation and is suitable for mono FM and SCA transmission. The other employs direct FM modulation and is required for stereo transmission.

Collins Radio Company 5, 10, and 20 kw transmitters are shown in Fig. 33. These models all employ a tetrode final amplifier and a tetrode driver stage. The rf circuitry is simplified by locating the driver stage so a common network is used to couple the driver plate to the final amplifier grid as shown in Fig. 34. An automatic rf power output control is incorporated which

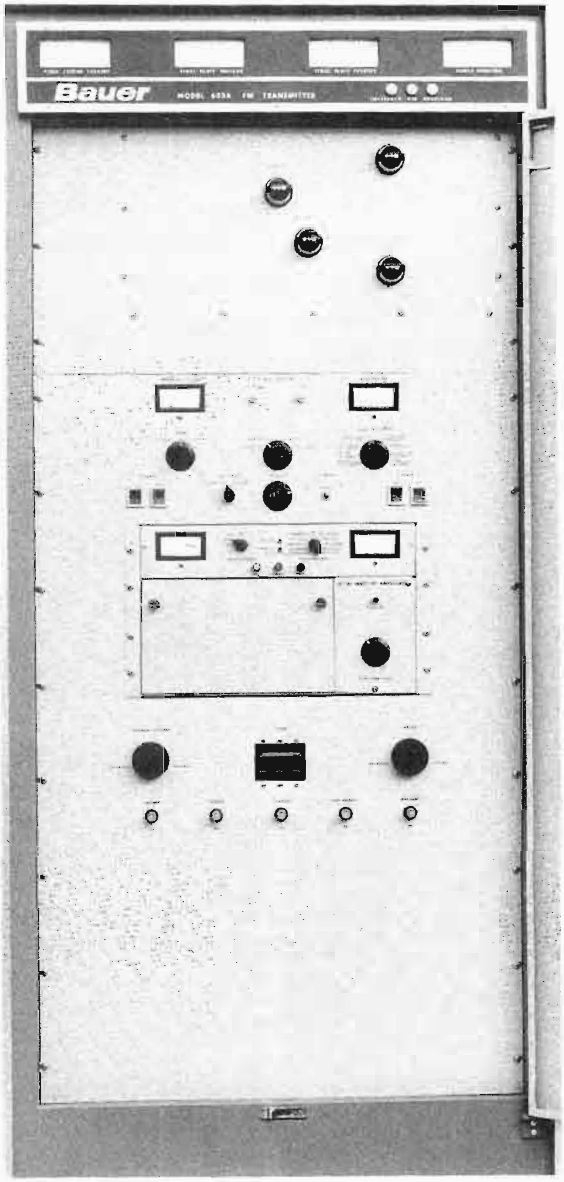


Fig. 29. Bauer Model 603 3- and 5-kw transmitter with front door open.

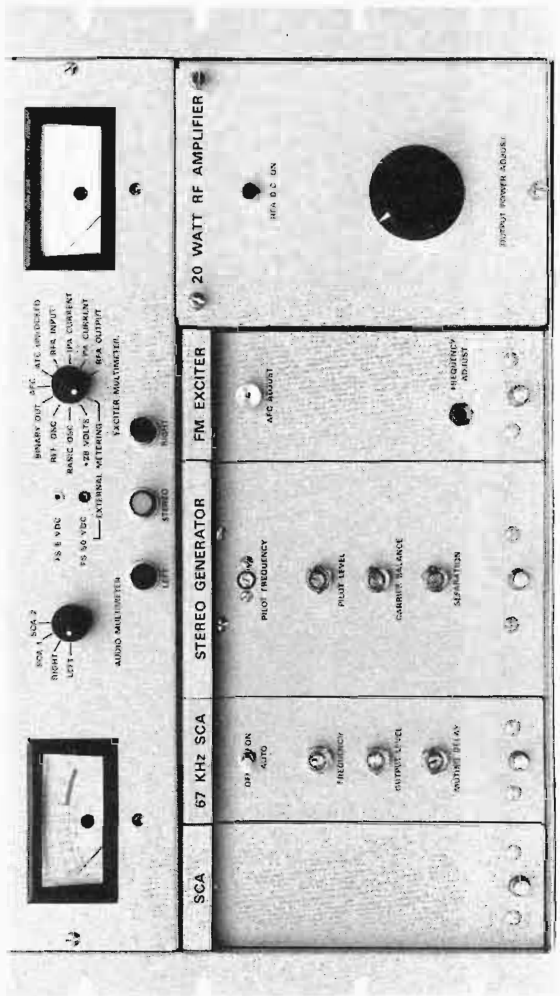


Fig. 30. Bauer Model 660 FM Exciter.

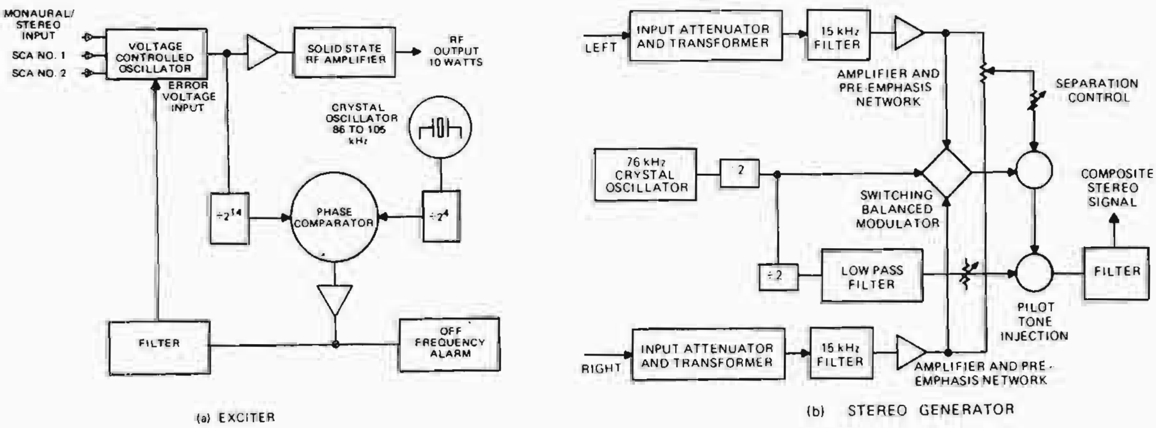
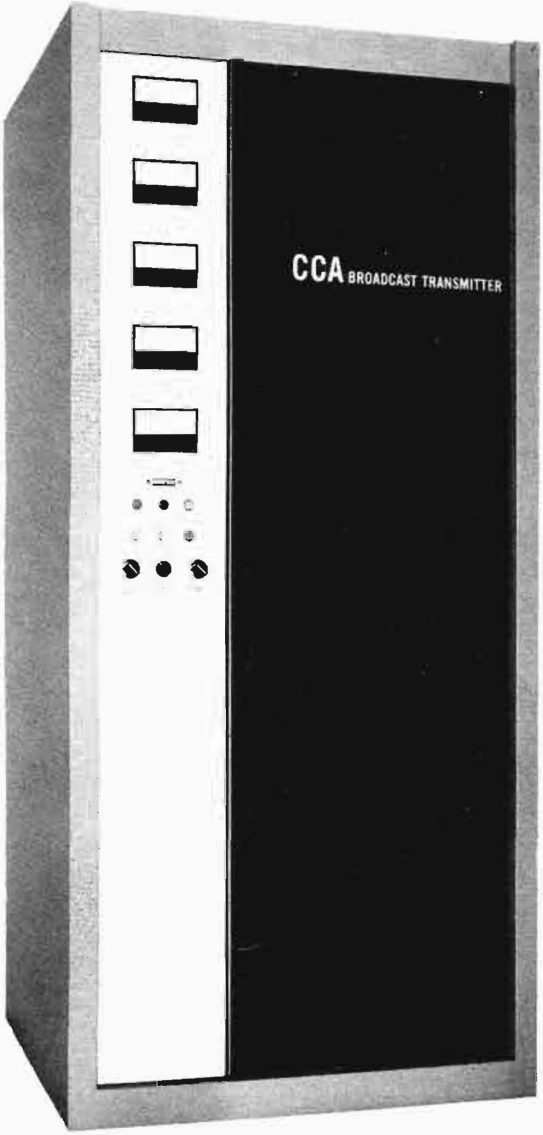


Fig. 31. Block diagrams of Bauer Model 660 FM Exciter and Stereo Generator.



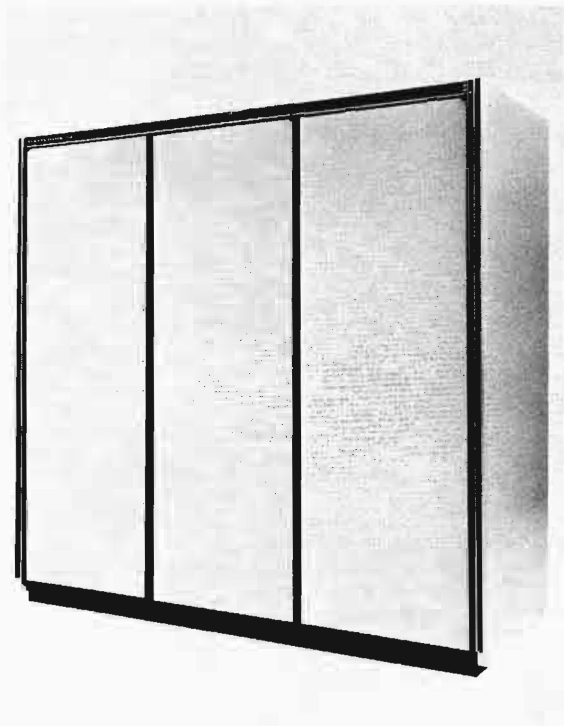


Fig. 33. Photograph of Collins, 5-, 10-, and 20-kw transmitters.

Fig. 32. View of CCA Electronics Corporation 5-, 10-, and 20-kw transmitters.

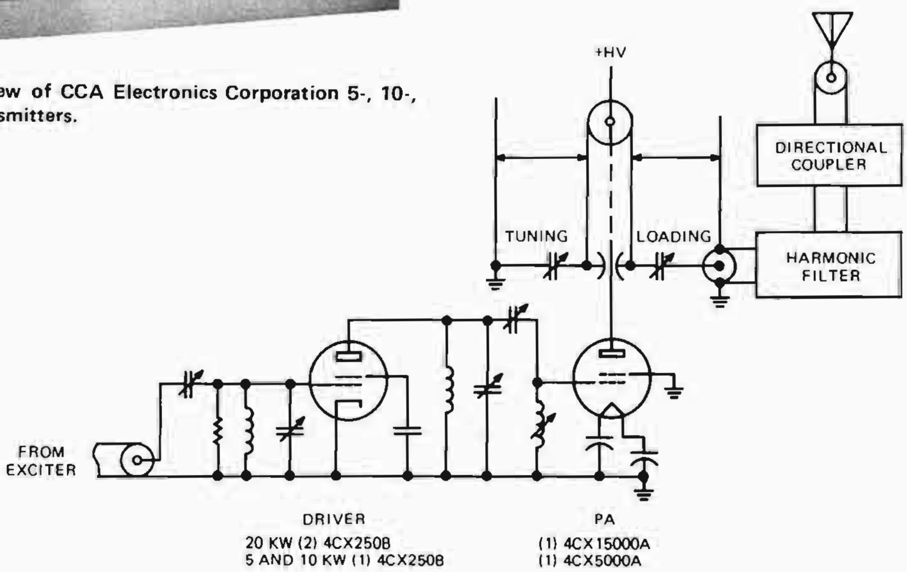


Fig. 34. Circuit diagram of Collins 5-, 10-, and 20-kw power amplifiers.

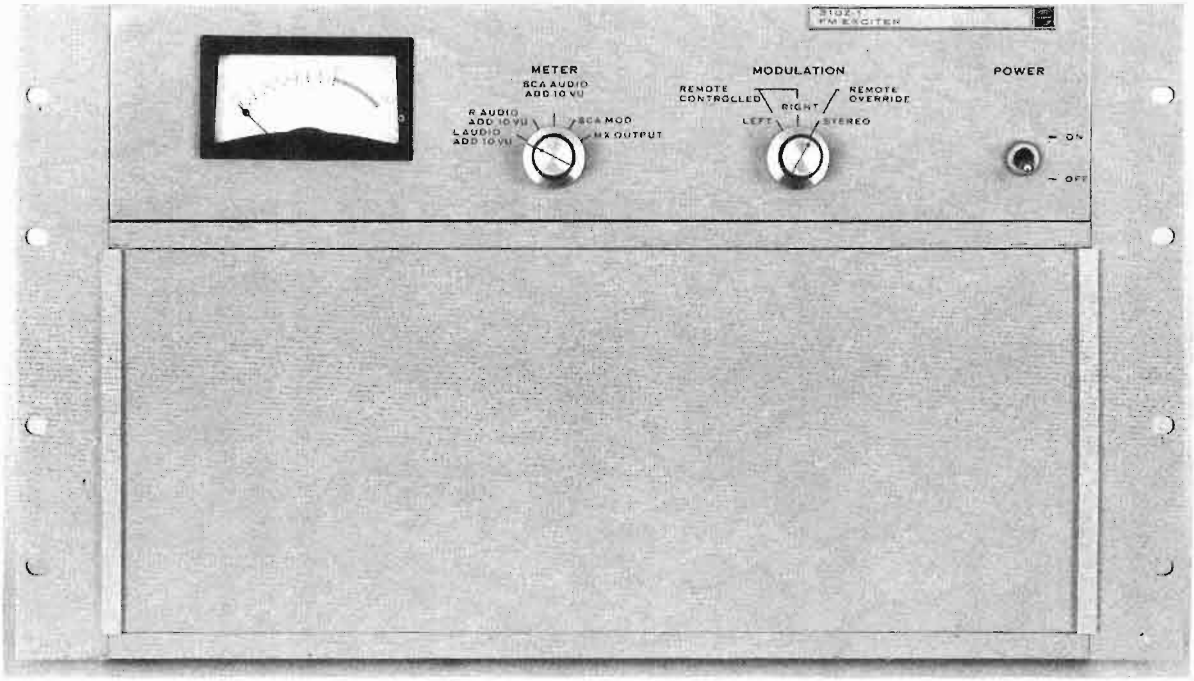


Fig. 35. Collins Model 310Z-1 Exciter.

keeps the output constant through wide variations in primary line voltage. Collins also manufactures transmitters for the 250 watt, 1 kw, and 2 kw power levels. The Collins exciter shown in Fig. 35 employs direct FM of an oscillator operating at 14 MHz. This is converted up to the desired carrier frequency as shown in Fig. 36. The AFC circuit uses a frequency comparison technique where the modulated oscillator frequency and the reference 14 MHz crystal oscillator are alternately sampled at about a 5 Hz rate. Most of the exciter circuitry is contained in six plug-in cards, each containing a major circuit function. The stereo generator employs the switching matrix method of stereo signal generation. The stereo generator and SCA generator are optional units which may be plugged into the main exciter at any time.

The Gates FM-20H transmitter and TE-1 exciter, shown in Fig. 37 and Fig. 38, are manufactured by Gates Radio Company, a subsidiary of Harris Intertype Corporation. Gates manufactures transmitters for all power requirements. The Gates exciter employs modular construction as shown in the photograph. The basic exciter is prewired to accept the SCA and Stereo units without modification. An overall block diagram of the exciter is shown in Fig. 39. Direct FM is employed. Two SCA units can be installed

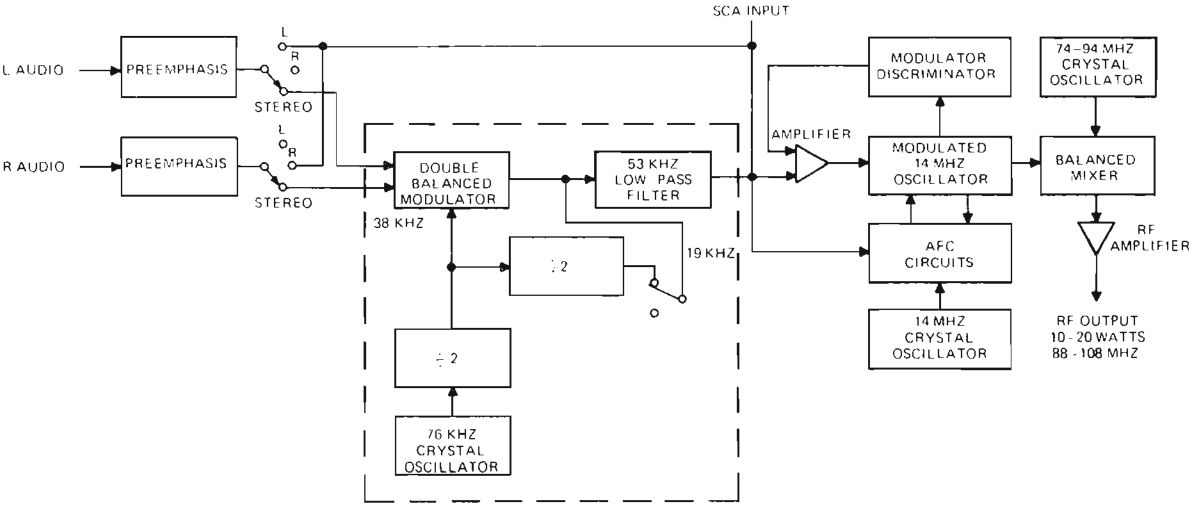


Fig. 36. Block diagram of Collins 310Z-1 Exciter.

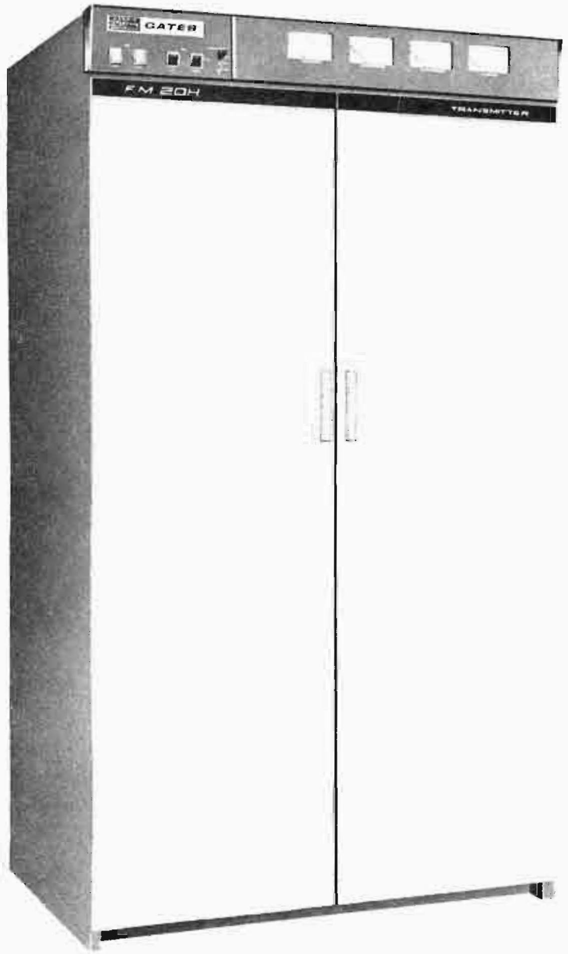


Fig. 37. Gates FM-20H Transmitter.

in addition to the stereo unit. The 41 kHz SCA unit, if installed, is automatically disabled when stereo operation is desired. More detail of the SCA generator is shown in Fig. 40. Two oscillators are used, one operating at 900 kHz and the other operating at either 941 or 967 kHz. They are modulated in opposite directions and their outputs are mixed to obtain the difference frequency. The stereo generator block diagram is shown in Fig. 41.

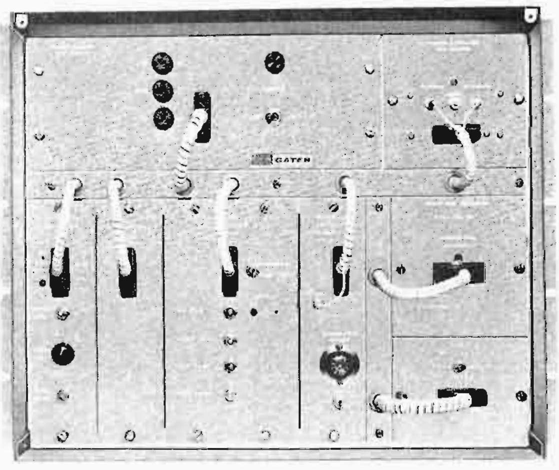


Fig. 38. Gates TE-1 Exciter.

The stereo matrix is in the main exciter so the stereo generator receives the L+R and L-R audio inputs and generates the composite stereo signal including insertion of the pilot carrier. The AFC operation is shown in Fig. 42. The output of the crystal oscillator is tripled to produce an output 200 kHz lower than carrirer frequency. This is mixed with the modulated oscillator output frequency to obtain the 200 kHz output which is processed and applied to a pulse counting type circuit to produce a ±dc voltage to control the center frequency of the modulated oscillator.

A photograph of the RCA BTF-40E 40-kw FM Transmitter is shown in Fig. 43. The output of a pair of 20 kw amplifiers is combined to produce the 40 kw. RCA also produces lower power transmitters. The BTE-15A FM Exciter is shown in Fig. 44. Block diagrams of the exciter and BTS-1B stereo generator are shown in Fig. 45 and Fig. 46. The reference crystal oscillator operates at 2^{-10} or $\frac{1}{1024}$ of the carrier frequency. Both are divided down to a common frequency in the 6 kHz region where they are compared with a phase detector. The phase detector output provides the AFC control voltage to keep the modulated oscillator on frequency. The stereo generator employs the switching type matrix for generating the composite stereo signal.

An interior view common to the Visual 10, 15, and 20 kw transmitters manufactured by Visual Electronics Corporation is shown in Fig. 47. The block diagram for these transmitters is shown in Fig. 48. Visual manufactures various models to cover any power requirement. They obtain 40 kw by combining the output of two 20 kw transmitters. All transmitters use zero bias triodes in grounded grid operation except for the 250 watt transmitter. The 1 kw model and the 3/5 kw models employ a tetrode driving a triode final power amplifier. The 5/7.5/10 kw model and 10/15/20 kw basic models employ a tetrode and two grounded-grid zero bias triode stages as shown in Fig. 48. The Visual direct FM exciter and block diagram is shown in Fig. 49 and Fig. 50. The frequency modulated oscillator operates on 21.5 MHz that is heterodyned up to the desired carrier frequency. For AFC control the output of the modulated oscillator is converted down to 400 kHz where a counter detector is employed to generate the AFC voltage.

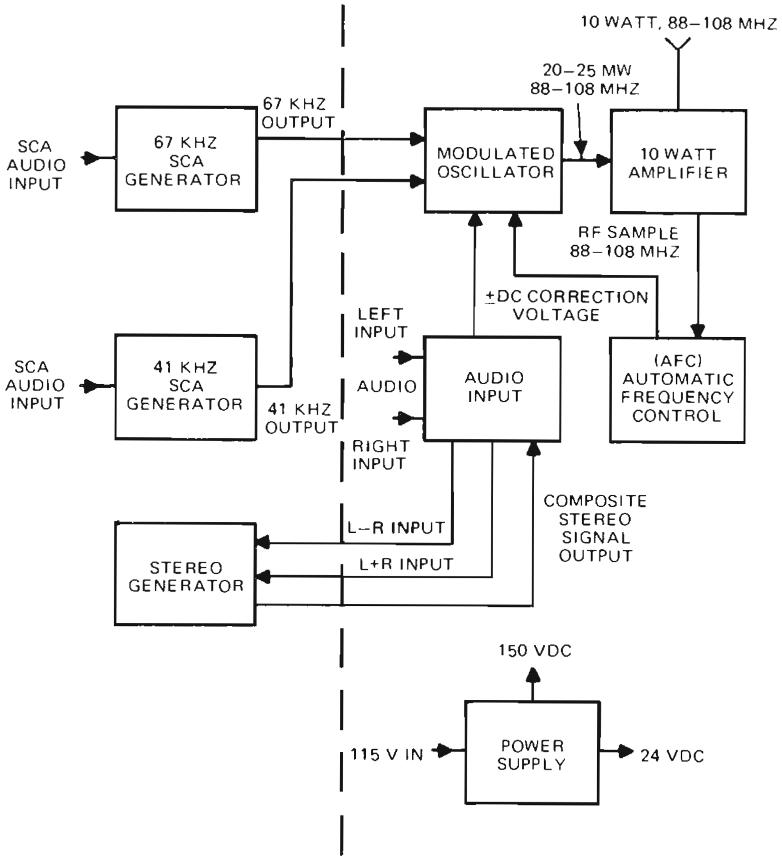


Fig. 39. Block diagram of Gates TE-1 Exciter.

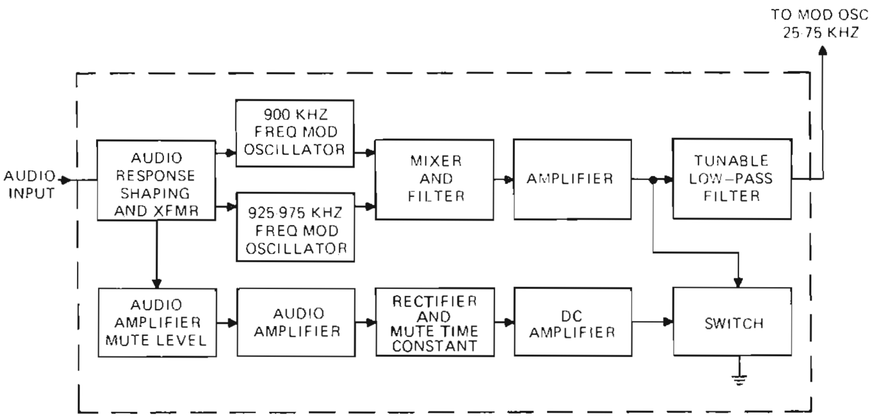


Fig. 40. Block diagram of Gates SCA generator circuit.

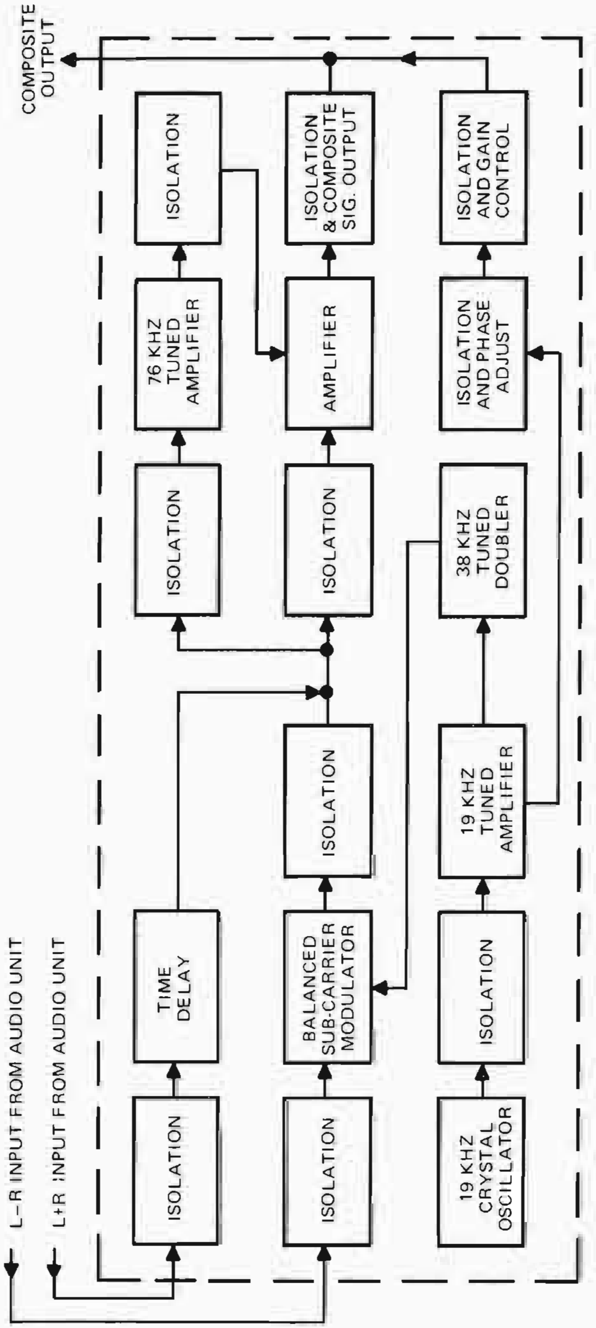


Fig. 41. Block diagram of Gates Stereo generator circuit.

PERFORMANCE MEASUREMENTS

Measurements required to insure high quality transmissions from an FM station fall into three general categories. These are:

a. Routine operational measurements required in the day-by-day operation of the station.

b. Proof-of-performance measurements required at least once each year and prior to application for license renewal;

c. Maintenance measurements.

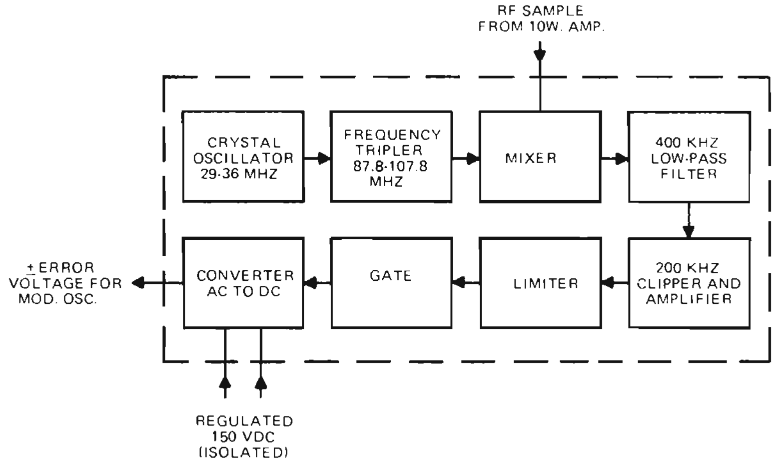


Fig. 42. Block diagram of Gates AFC circuit.

Routine Operational Measurements

Certain parameters are considered by the FCC to be important enough to justify almost continuous observation. Especially important are the modulation level, carrier frequency, and output power level. The latter two parameters, among others discussed below, must be logged at least once every 30 min.

The measurement of percentage modulation must be accomplished with a modulation monitor which has been type-approved for the applicable modulation mode or modes employed. At this writing much interest and concern has developed throughout the broadcasting industry as to the best method for the determination of modulation percentage for complex program material. The ability of meter movements to follow short-

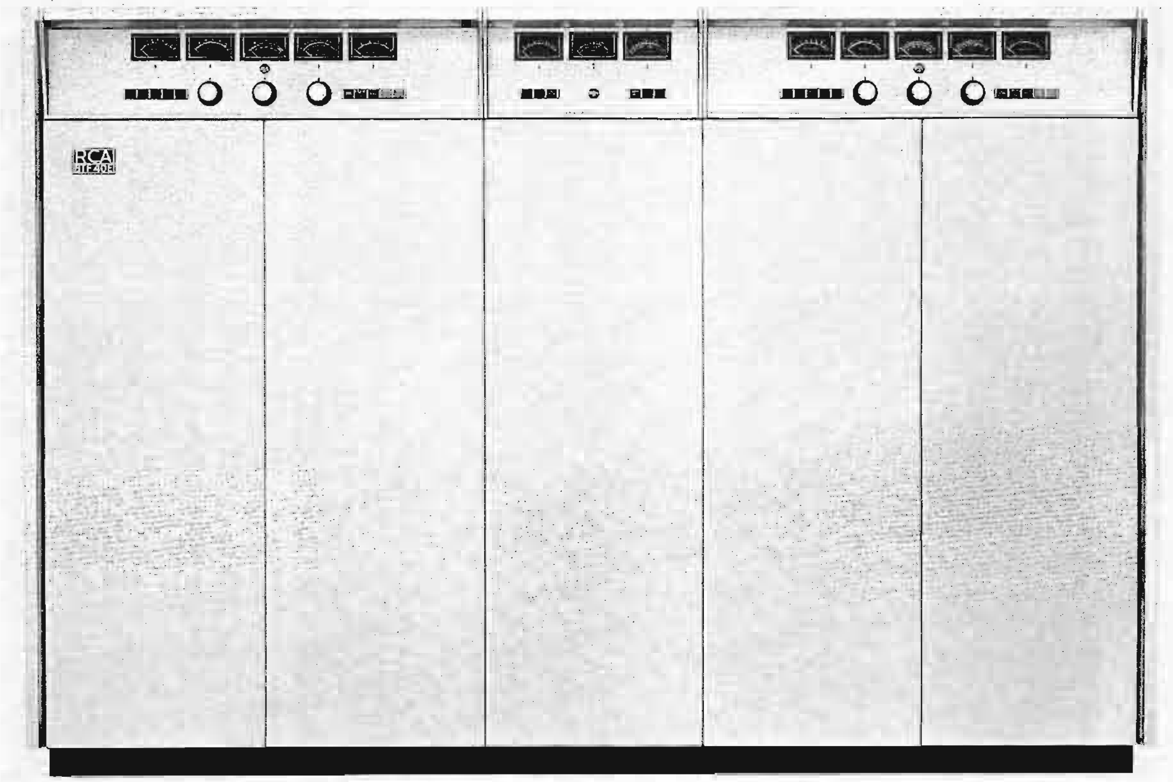


Fig. 43. RCA BTF-40E 40-kw transmitter.

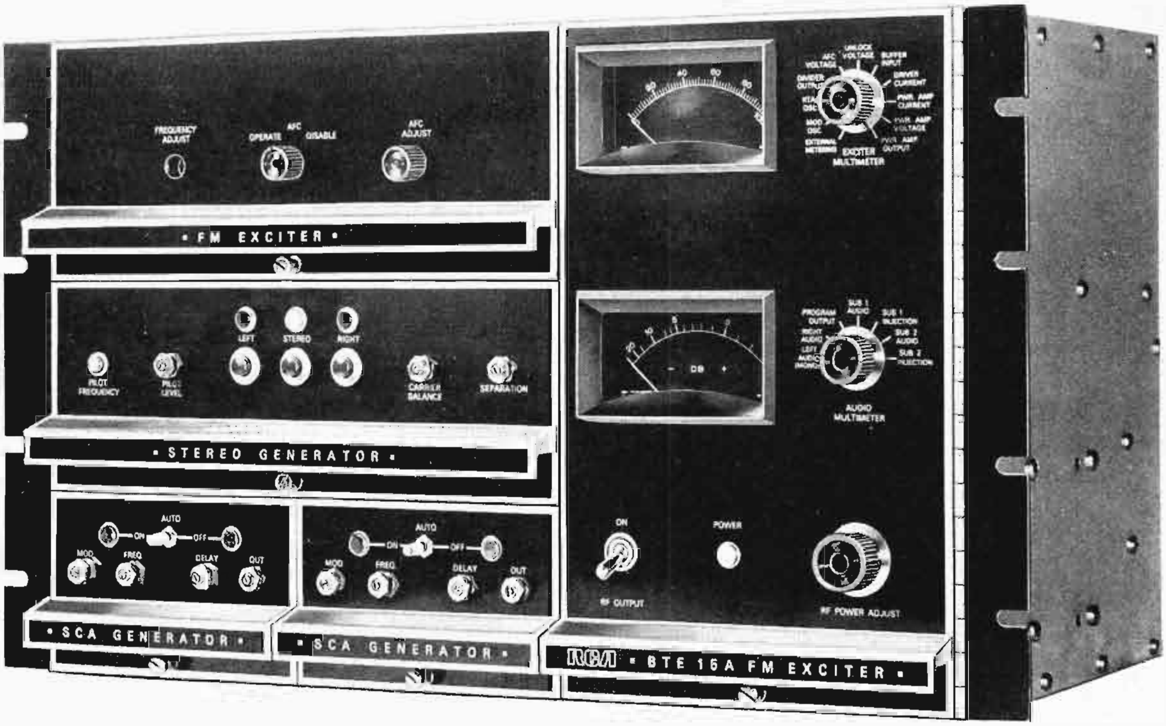


Fig. 44. RCA BTE-15A FM exciter.

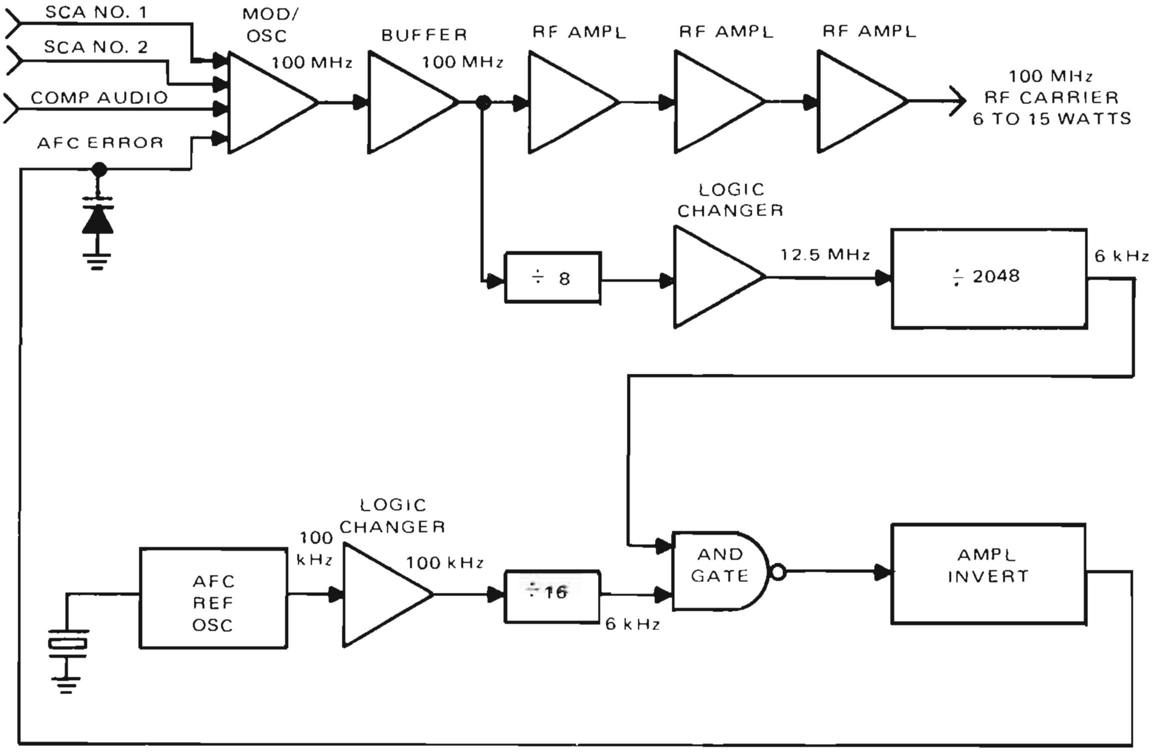


Fig. 45. Block diagram of RCA BTE-15A FM exciter.

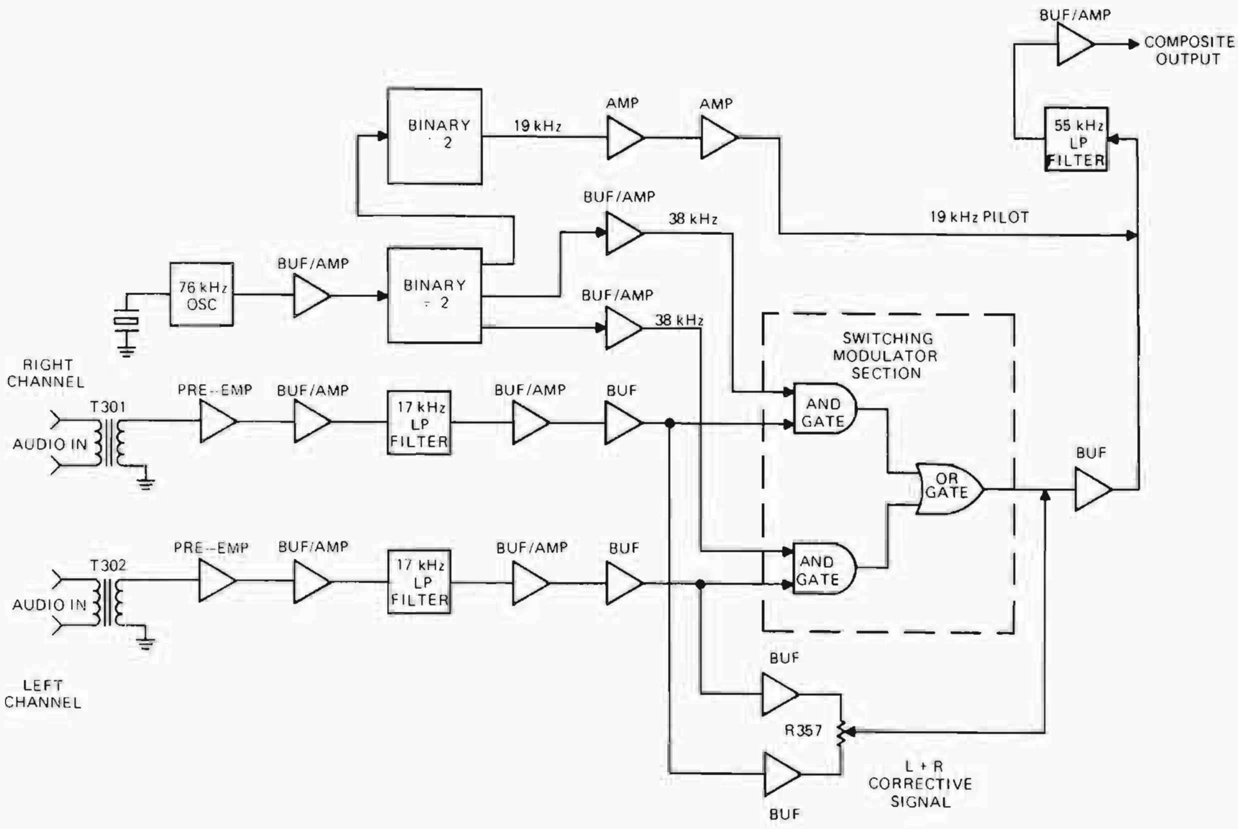


Fig. 46. Block diagram of RCA BTS-1B stereo generator.

duration, nonrepetitive peaks accurately has received special attention. The results of various tests have generally shown that meter movements cannot follow modulation peaks with the required accuracy.

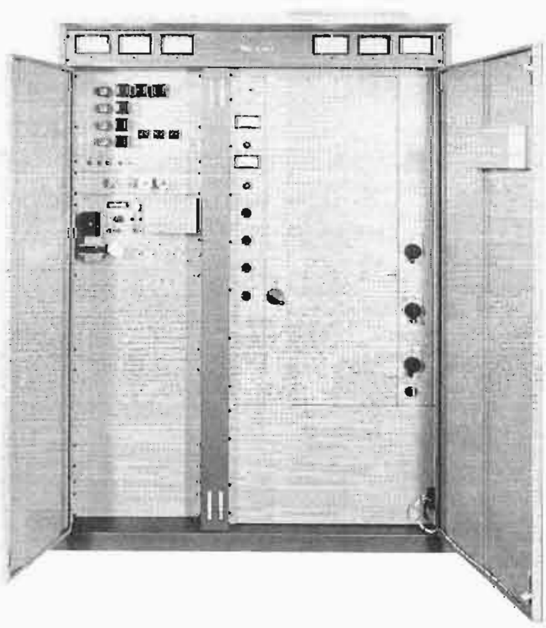


Fig. 47. Photograph of Visual Electronics Corporation, 5-, 10-, and 20-kw transmitters.

For this reason, modulation monitors are required to have, in addition to the meter, a peak-indicating device, such as a flashing light which can be preset to flash for modulating levels between 50 percent and 120 percent. This device must be used instead of the meter to determine overmodulation conditions in the transmitter.

Average carrier frequency must be measured with a type-approved frequency monitor. These monitors fall into two categories, analog and digital. The trend is toward the digital meter because of its inherent accuracy and ease of use.

The methods for determining rf output power are specified in Paragraph 73.267 of the FCC Rules and Regulations, which are reproduced in the section entitled FCC Transmission Standards. An accurately calibrated directional wattmeter provides an excellent means of making a direct measurement of rf output power. This method of operation is explained in the Directional Wattmeter section. The directional wattmeter is seldom used as the primary rf power determining method because of the requirement for recalibrating every six months. Use of the indirect method avoids this requirement. If the equipment contains a directional wattmeter, it should be used as

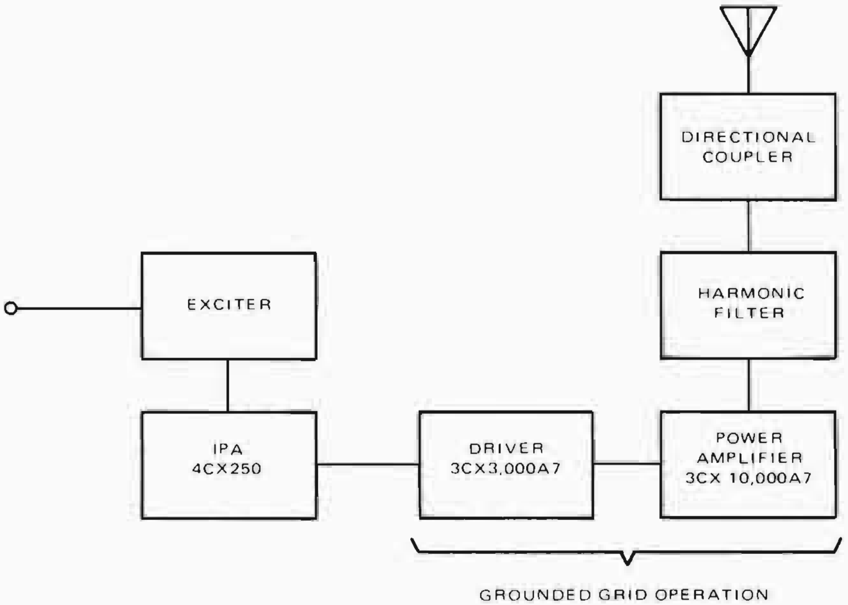


Fig. 48. Block diagram of Visual DFM-20K-B 20-kw transmitter.

a check to assure that rf output is now low, which could be caused by incorrect tuning, changing antenna conditions or a weak tube.

In the indirect method, output power is calculated from a measurement of input power multiplied by the efficiency factor of the final amplifier stage. The efficiency factor is provided by the transmitter manufacturer and must be applicable to the particular frequency and power level in use. The power input to the final amplifier stage is the product of plate voltage and plate current. These latter two parameters are read from meters provided as parts of the transmitter.

All FM stations must log certain transmitter parameters at least once every 30 min. Required entries are:

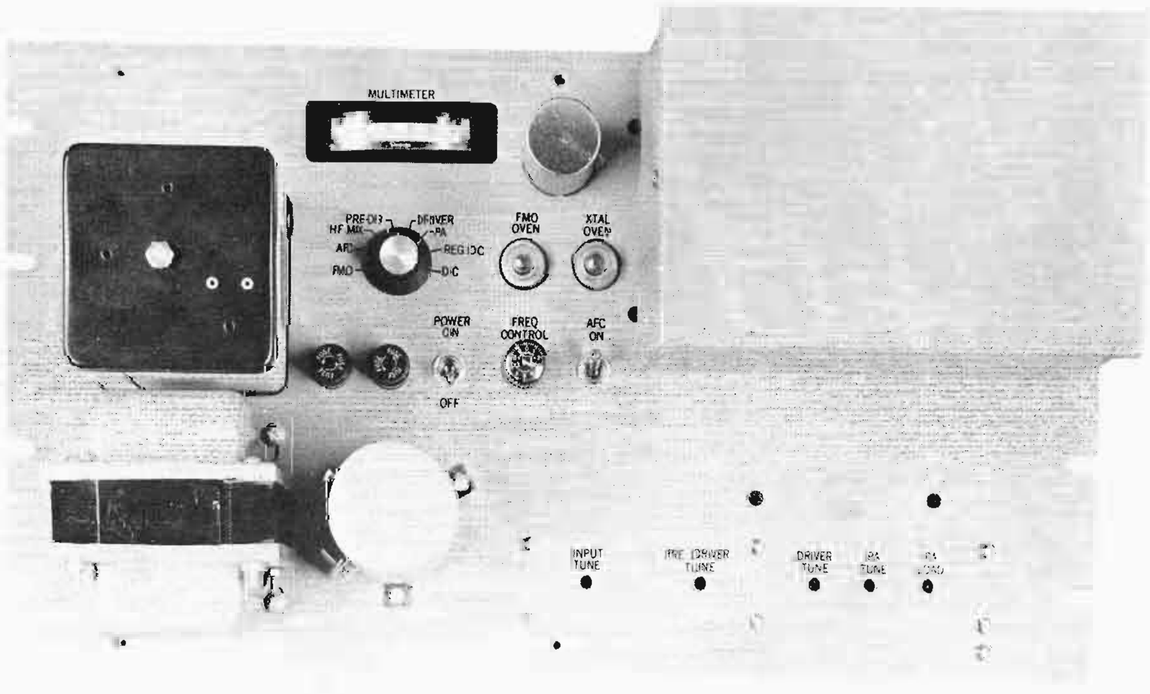


Fig. 49. Photograph of Visual direct FM exciter.

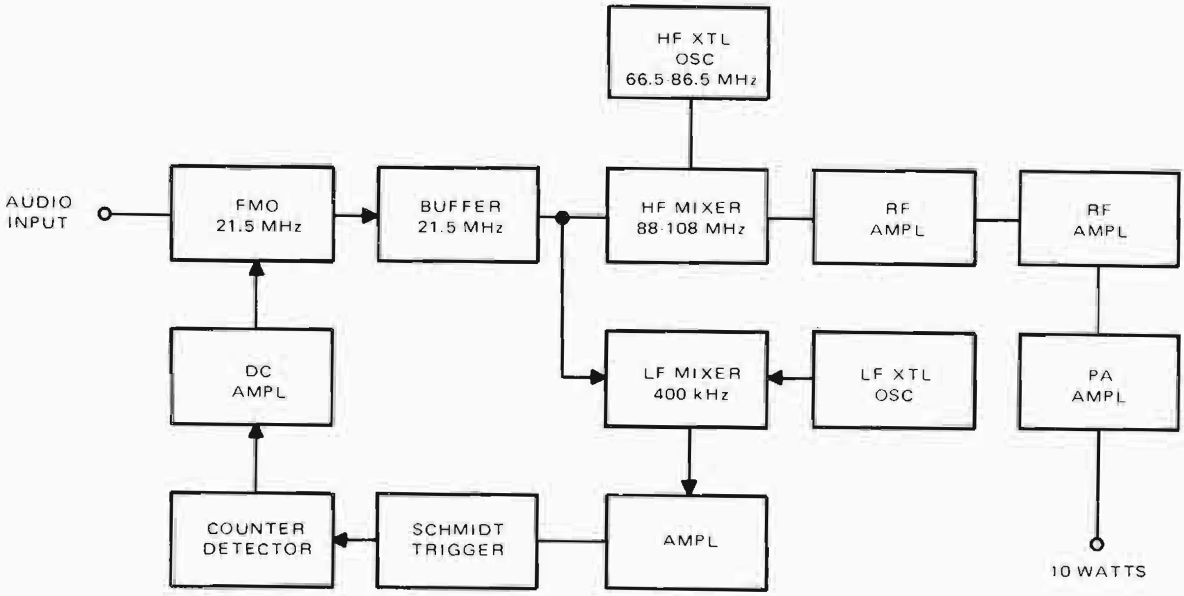


Fig. 50. Block diagram of Visual DFM-10A/B 10-watt FM broadcast exciter/transmitter.

1. Final amplifier plate voltage;
2. Final amplifier plate current;
3. Rf transmission line current, voltage, or power;
4. Average carrier frequency.

Other parameters, such as pilot subcarrier frequency and SCA subcarrier frequency, require less frequent measurement and logging. Paragraphs 73.283, 73.295, and 73.297 of the FCC Rules and Regulations should be referred to for these additional requirements. Logs must be retained by the licensee for a period of two years.

Proof of Performance Measurements

Paragraph 73.254 of the FCC Rules and Regulations defines the requirements for an FM proof-of-performance. This proof must be made at least once each year and during the four-month period preceding the date of filing application for renewal of the station license. The proof-of-performance data must be kept on file at the transmitter for a period of two years.

As of this writing, the requirements for a stereo proof-of-performance have not been defined and only monophonic measurements are required for the official proof-of-performance. Stereo stations are required to meet the requirements of Paragraphs 73.317 and 73.322 on a continuous basis, however, and it is recommended that a stereo proof-of-performance be made at least annually as a matter of good engineering practice. Stereo measurements are described later under the section that describes maintenance measurements.

The current requirements for a proof-of-performance test specify the following measurements:

1. Audio frequency response;
2. Audio frequency harmonic distortion;
3. FM signal-to-noise ratio;
4. AM noise level.

Fig. 51 is a block diagram of a typical test set-up for proof-of-performance measurements. All measurements are made on the composite system from microphone terminals of the console to the transmitter output. All normal program circuits, with the exception of limiting and compression amplifiers, must be included in the measurements. If the compression and limiting amplifiers have switches that convert them to linear, fixed-gain operation, the measurements should be made with the limiters and compression amplifiers in the linear fixed-gain mode of operation. If not, they should be removed from the circuit.

Audio frequency response measurement. Audio frequency response is measured in reverse, that is, a constant output modulating level is maintained for all modulating frequencies by adjusting the amount of attenuation between the audio generator and the microphone input terminals. This is necessary because of the rising response due to pre-emphasis. Frequency response data is taken at three levels of modulation: 25 percent, 50 percent, and 100 percent. The audio voltmeter which measures the audio generator output voltage is used to maintain constant voltage level versus frequency at the generator output terminals. The attenuator dials are adjusted for each modulating

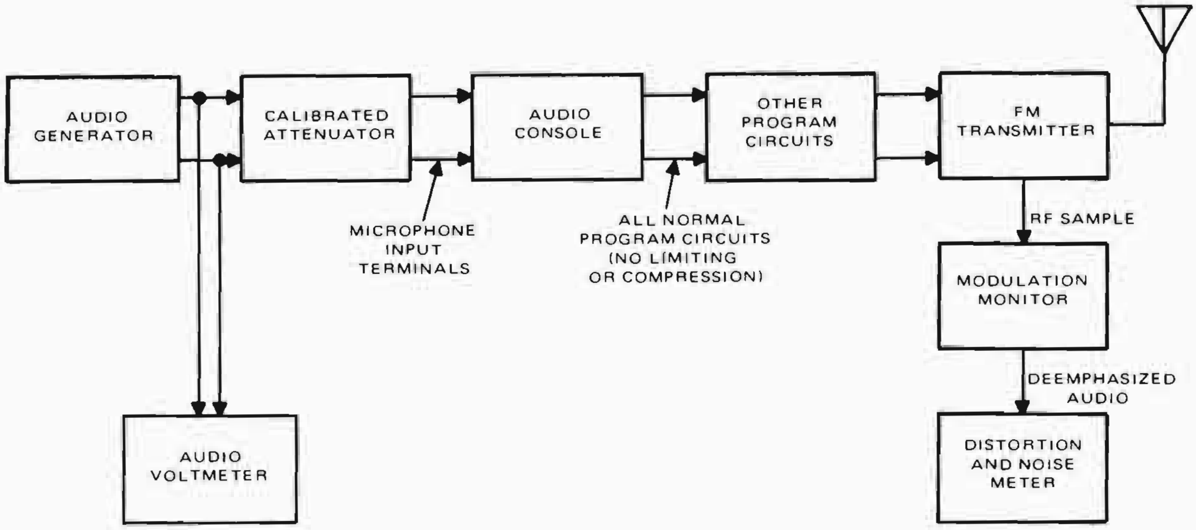


Fig. 51. Block diagram of test set-up for proof-of-performance measurements.

frequency to maintain the desired modulating level and the attenuator readings, in decibels, are recorded. Readings should be taken for the following modulating frequencies: 50, 100, 400, 1,000, 5,000, 7,500, 10,000, and 15,000 Hz. (7,500 Hz is not required by the FCC Rules and Regulations but is needed when the data is plotted within the limit curves).

When attenuation in decibels is plotted versus frequency, the 75-microsecond pre-emphasis curve is obtained if the system frequency response is perfect. Deviations from the ideal response are permitted to an extent which allows the measured curve to be fitted between the limit curves shown in Fig. 4. The procedure for doing this is to subtract or add the same number of decibels from each of the measured values. This process may be repeated until a fit is obtained. If it is impossible to obtain a fit by subtracting or adding the same value of attenuation from all measured values, the system frequency response is inadequate and adjustments must be made.

Audio frequency harmonic distortion measurement. Harmonic distortion of the system from microphone input terminals to transmitter output is measured by modulating the transmitter with sinusoidal modulating signals having low distortion and observing the harmonic content at the output of the modulation monitor. For this measurement, pre-emphasis is used in the transmitter and de-emphasis is used in the monitor. Measurement equipment must pass de-emphasized harmonics through 30 kHz.

The normal distortion meter used in this test reads not only harmonic distortion but also noise in the audio passband. If the total harmonic distortion and noise is within the harmonic distortion limits, the system is assumed to meet its harmonic distortion requirements.

Harmonic distortion must be measured under the following conditions:

1. For modulating frequencies of 50, 100, 400, 1,000, and 5,000 Hz at modulating levels of 25, 50, and 100 percent modulation;

2. For modulating frequencies of 10 kHz and 15 kHz at a modulating level of 100 percent.

The preceding measurements must show that the system harmonic distortion is less than 3.5 percent for modulating frequencies between 50 and 100 Hz, less than 2.5 percent for modulating frequencies between 100 and 7,500 Hz, and less than 3 percent for modulating frequencies between 7,500 and 15,000 Hz. If distortion levels greater than these are measured, the system requires adjustment.

FM signal-to-noise ratio measurement. FM signal-to-noise ratio of the system is measured from microphone input terminals to the transmitter output. The residual noise level at the monitor output is measured with a distortion and noise meter or with an audio voltmeter. For this measurement, pre-emphasis is employed in the transmitter and de-emphasis in the monitor. The residual audio noise level is referenced to the signal level caused by 400 Hz modulation at the 100 percent level.

The procedure for making the FM signal-to-noise ratio measurement is as follows:

1. Modulate the transmitter with a 400 Hz sine wave applied at the microphone input terminals of the console and set the level for 100 percent modulation;

2. Read and record the audio signal level appearing at the monitor monophonic output terminals. If the monitor has audio metering capability, the meter gain should be set for a 0-dB reference level according to the manufacturer's instruction;

3. Remove the modulation and terminate the console audio input terminals with a resistor equal to the normal microphone output impedance (usually 150 ohms).

4. Read and record the residual audio noise voltage in decibels below the 400 Hz signal level.

The measured signal-to-noise ratio must be at least 60 dB.

AM noise level measurement. Residual amplitude modulation of the transmitter output is measured with all audio circuits except compression amplifiers and limiters connected. For this measurement, an AM detector is required. Most FM modulation monitors include an AM detector for this purpose. The detector must include 75-microsecond de-emphasis of its output. AM noise measurements must be 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 this equipment would modify the residual AM noise level present.

The FCC Rules and Regulations require residual AM noise to be 50 dB below the level which represents 100 percent amplitude modulation of the carrier. Since the transmitter cannot be amplitude modulated, this reference must be established indirectly by a measurement of the rf carrier voltage. Refer to the instructions of the detector manufacturer to determine the reference level. Generally, the reference level is determined by setting a carrier level meter to a specified reading at which setting, the reference level is stated.

Maintenance Measurements

This section describes measurements which must be made as a matter of good engineering practice if the operation of the station is to comply fully with the FCC technical standards. At this writing, the FCC Rules and Regulations have not established a requirement for these measurements to be repeated at regular intervals, but the operating parameters concerned must be maintained within specification at all times. It is left to the station engineer to determine a schedule which will meet this requirement for his particular equipment and situation.

Several of the tests to be described apply to stereo transmission and others to SCA transmission. It is reasonable to expect that some of the tests in this section may be required in the future as a part of proof-of-performance tests for the applicable mode or modes of transmission.

Stereophonic channel separation measurement. Channel separation between the left and right audio channels is measured from microphone input terminals to transmitter output by using a type-approved stereo modulation monitor attached to the transmitter output sampling loop. Since channel separation is a very difficult parameter to measure accurately, it is recommended that rf amplifiers, which sometimes are inserted ahead of the monitor, be used with extreme care because they may have inadequate phase and amplitude characteristics for precise channel separation measurements.

The procedure for measuring channel separation is as follows:

1. Apply a sinusoidal modulating signal to the left microphone input terminals at a level sufficient to cause 100 percent total modulation (including pilot carrier);

2. Record the left signal level appearing at the left output of the monitor as the 0-dB reference level;

3. Transfer the modulating tone to the right channel, adjusting for 100 percent total modulation. Terminate the left channel in a resistance equal to the microphone output impedance;

4. Record the residual level in the left channel output of the monitor. This reading should be expressed in decibels below the previous signal level reference;

5. Repeat the above procedure for the right channel;

6. Channel separation should be measured for the following test frequencies: 50, 100, 400, 1,000, 5,000, 7,500, 10,000 and 15,000 Hz;

7. If the monitor de-emphasis can be switched out, better accuracy at the higher modulating frequencies can be obtained because the signal-to-noise ratio at the monitor output is greater (due to increased high frequency signal level).

All readings must be at least 29.7 dB to comply with stereophonic transmission standards.

Stereophonic frequency response measurement. Stereophonic frequency response should be measured from microphone input terminals to transmitter output in a manner similar to that used for monophonic measurements. Sinusoidal modulation is applied to one channel at a time. An input attenuator between the audio generator and the console is adjusted to maintain constant output levels of modulation for various modulating frequencies. When input attenuation in decibels is plotted versus modulating frequency, the pre-emphasis curve is obtained. This curve must fit between the limit curves shown in Fig. 4.

Frequency response data should be taken for both channels at modulating frequencies of 50, 100, 400, 1,000, 5,000, 7,500, 10,000 and 15,000 Hz and for total modulation levels (including pilot) of 25, 50, and 100 percent.

Stereophonic signal-to-noise ratio measurement. The FCC Rules and Regulations have not specified directly the signal-to-noise ratio required in the left and right channels, but instead have specified the signal-to-noise required in the main channel and in the stereo subchannel. The required signal-to-noise ratio in each of these channels is 60 dB.

Stereophonic modulation monitors contain filters to break the baseband spectrum into main channel and subchannel segments. The main channel noise may be measured with such a monitor but, unfortunately, subchannel noise may be impossible to measure because of the existence of the stereophonic subcarrier. The subcarrier, which falls within the passband of the subchannel filter, may be 20 dB greater than the noise level to be measured, since the FCC Rules and Regulations permit subcarrier levels as great as -40 dB.

It would appear that the only practical way to measure stereophonic signal-to-noise ratio is by the direct observation of the noise at the left and right output of the modulation monitor. This can be accomplished quite easily, but the requirements have not been defined for either the monitor or the transmitter. It is reasonable to assume that stereophonic signal-to-noise requirements should be somewhat lower than monophonic signal-to-noise requirements because of the increased noise bandwidth, slightly lower levels of signal modulation, and because of additional noise introduced in the monitor stereo demodulator. A measured value of over 50 dB signal-to-noise ratio in the left and right monitor output should be obtained for high quality FM broadcasting service.

Stereophonic distortion measurements. The procedure for measuring stereophonic is almost identical to the monophonic procedure. The audio test signals should be injected into the console microphone input terminals with one channel modulated at a time.

Measurements of each channel should be made for the following modulation conditions:

1. For modulating frequencies of 50, 100, 400, 1,000, and 5,000 Hz and total modulating levels, including pilot, of 25, 50, and 100 percent modulation;
2. For modulating frequencies of 10 kHz and 15 kHz and total modulating levels of 25, 50, and 100 percent modulation.

The measured distortion should fall within the performance specifications required for monophonic transmissions.

Stereophonic subcarrier suppression measurements. The measurement of subcarrier suppression is accomplished with the use of a stereophonic modulation monitor having a narrow 38-kHz bandpass filter included for this purpose. The FCC Rules and Regulations require residual 38-kHz subcarrier to be at least 400 dB below the 100 percent modulation level. The test procedure is to establish, first, a reference level for 100 percent modulation by modulating with either a main channel or subchannel signal (according to the monitor manufacturer's instruction). This modulation is generated by applying equal in-phase signals to the left and right inputs for main channel modulation or by applying equal but out-of-phase inputs to obtain subchannel modulation.

After the reference level is established, the monitor is switched to the stereophonic subcarrier measurement position to read residual subcarrier level with respect to the previously established reference level. The subcarrier level should be measured for various modulation conditions to insure that subcarrier holds with modulation. It is recommended that the test be made for modulating frequencies of 5,000, 10,000, and 15,000 Hz and for left only, right only, L = R and L = -R modulation.

Modulating frequencies less than 5,000 Hz may cause trouble because the subcarrier filter in the monitor may have inadequate selectivity to separate the subcarrier from the subchannel sidebands.

Stereophonic crosstalk measurements. Crosstalk between the main channel and the stereophonic subchannel is specified in Paragraph 73.322 of the FCC Rules and Regulations. The exact meaning and intent of this specification has received much discussion throughout the industry since the beginning of FM stereophonic multiplex operation. At this writing, the controversy has not been settled.

The original specification was probably written with a matrix scheme in mind wherein the transmitter had an input for accepting main channel (L+R) information and a second input for accepting subchannel (L-R) information. In a system of this type, a measurement is easily accomplished by first applying modulation to one of the inputs and then the other.

Since the FCC Rules and Regulations were written, the two-input transmitter has all but vanished. The single-input, wide-band transmitter is now commonplace. In this system, the baseband stereo signal enters the transmitter at a single input. Herein lies the basic cause of confusion in making crosstalk measurements.

In order to produce a signal in the main L = R channel with none in the stereophonic L-R channel, the separate L and R inputs must be adjusted in amplitude and phase so the signal in the L-R stereo channel is in a deep null. The residual L-R signal must be considerably more than 40 dB below 90 percent modulation in order to be able to measure crosstalk products that are required to be at least that far down. In practice, there are separate high-pass filters, low-pass filters, or 19-kHz notch filters and the pre-emphasis network in the separate L and R audio circuits ahead of the stereo matrix circuit. It is neither practical nor necessary to require that they be sufficiently well-matched (within 0.1 dB and 1°) to allow testing with L-R input signals. The normal phase difference encountered in practice can be compensated for by employing a device to shift the phase and vary the amplitude of one of the audio inputs. It is simply adjusted to null the signal in the stereo channel. The residual signal is called crosstalk.

The same situation prevails in testing for crosstalk from the stereo into the main channel. The input phases and amplitudes must be adjusted slightly from the theoretical L-R condition to null the L+R main channel signal. About all this crosstalk test does is ensure that certain distortion products generated in the circuits following the stereo matrixing circuit are kept below the levels permitted for harmonic distortion.

Crosstalk as specified in Paragraph 73.322 is defined as "crosstalk into the main channel *caused* by a signal in the stereophonic subchannel" and "crosstalk into the stereophonic subchannel *caused* by a signal in the main channel." The audio gain mismatch discussed previously causes a distribution of signal power between the main channel and subchannel which has sometimes been referred to as "crosstalk." It is not. This "apparent crosstalk" is *not caused* by the presence of a signal in the other channel but is merely the normal result of a trivial gain or phase mismatch in the audio circuits.

Crosstalk from SCA into main channel measurement. The FCC Rules and Regulations require that any component in the frequency range, 50 to 15,000 Hz, which results from SCA operation must be at least 60 dB below the 100 percent modulating level. To test for this requirement, a monitor which has a main channel filter is required. The procedure is similar to the monophonic signal-to-noise measurement except that de-emphasis is not used in the monitor and that the SCA subcarrier is turned on and modulated fully during the noise measurement. For this test, the SCA injection level should be set to the level normally used and the SCA subcarrier should be modulated with various frequencies up to and including the highest to be used.

A reference level is established for 100 percent modulation by applying a 400-Hz sine wave at a level causing 100 percent modulation of the main channel. Readings of crosstalk and noise in the main channel are then made with the main channel microphone terminals terminated in a resistance equal to the microphone output impedance.

Crosstalk from SCA into stereophonic subchannel measurement. For stereophonic and SCA operation, the FCC Rules and Regulations require that any component in the frequency range 50 Hz to 53,000 Hz which is caused by SCA operation be at least 60 dB below the 100 percent modulation level.

Most modulation monitors include filters for noise measurement of the 50- to 15,000-Hz region and for the 23- to 53-kHz region but not for the overall 50- to 53,000-Hz region. It has become standard practice to measure the noise level in the two bands which the monitor measures rather than the overall region.

The procedure for measuring crosstalk into the stereophonic subchannel is similar to the main channel measurement except that it may be necessary to deactivate the stereophonic subcarrier for the measurement in order to observe noise levels at the -60-dB level.

Crosstalk from stereo into SCA subchannel measurement. The measurement of crosstalk in the SCA subchannel from the main and stereophonic subchannels is not required by the FCC Rules and Regulations. It is a necessity, however, for stations engaged in SCA broadcasting to make periodic measurements of this parameter to ensure good SCA performance.

The measurement of crosstalk into the SCA subchannel must be accomplished with a high quality, SCA modulation monitor that has been designed for the purpose. The average SCA receiver is not capable of testing transmitter performance because it typically has a much greater level of distortion than does the transmitter to be tested. It should also be realized that the transmitter may be adequate even though all receivers in the field show an intolerably high level of crosstalk. The composite system including transmitter, antennas, transmission path, and receivers must be investigated when crosstalk is experienced.

Crosstalk into the SCA channel should be tested at the transmitter output with the main and stereophonic subchannels modulated with various modulating frequencies from 50 to 15,000 Hz. The SCA subcarrier should be on but unmodulated for the measurements. Since 100 percent SCA modulation has not been defined, the reference level to which SCA crosstalk is compared is arbitrary. It has become somewhat standard to define SCA modulation in terms of absolute frequency deviation in kilowatts rather than as a percentage of subcarrier frequency.

INSTALLATION CONSIDERATIONS

Adequate planning and care in the installation of an FM broadcast transmitter and associated equipment will help avoid many problems that may be difficult and expensive to correct later, for example, poor grounds and ground loops may cause high noise levels.

Separate conduits or troughs should be provided for the audio and the ac wiring. A third conduit should be used if computer logic levels are employed for equipment control. These conduits or wiring troughs may be either overhead or below the cabinets. The ac wiring should be well separated from the audio pairs to prevent the induction of unwanted noise into the audio circuits.

All audio shields should be grounded at only one point. This point is the one found experimentally to give the lowest noise pickup. The equipment racks should be connected together by copper straps at least 2 in. wide and tied to a good earth ground at one point. If a good ground screen is not available, a ground can be provided by driving four or five copper ground rods 8 to 10 ft. long into the ground with a spacing of about 3 ft. These ground rods should be tied together with copper strap which is at least 2 in. wide also. The wide strap connecting the equipment to the earth ground should be as short and direct as practical.

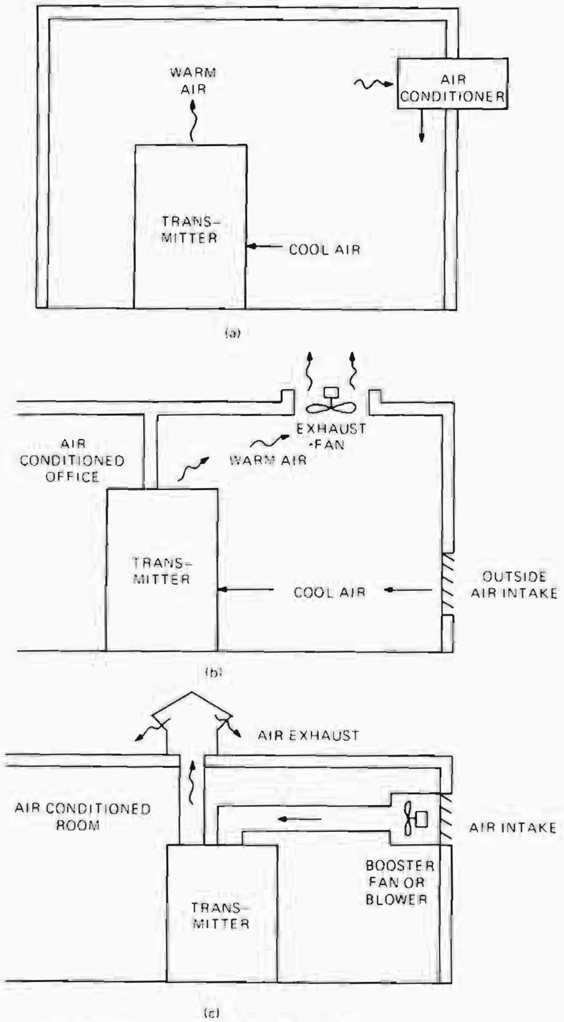


Fig. 52. Three methods of providing cooling air for the transmitter.

It is often difficult to remove rf from the equipment by grounding because at FM carrier frequencies, nearly any connection to an earth ground has an appreciable impedance. The best way to keep rf out of sensitive low level circuits is by keeping them enclosed in an rf shield and by filtering leads that enter the shielded units when necessary. Filters in the audio lines may be made up of small rf chokes and disc capacitors.

For stereo transmission, it is necessary to keep L and R audio lines phased properly. Correct phasing must be maintained throughout the station from the microphones, tape machines, and turntables through all of the audio equipment to the exciter audio input terminals.

The equipment should be located and arranged to provide sufficient room around it for easy access during servicing and maintenance.

A very important consideration in locating the transmitter is provision for cooling air. As a rough approximation, it can be assumed that the overall efficiency of the transmitter is a little less than 50 percent. In other words, it generates more kilowatts of heat than it does rf power output.

Fig. 52a shows a transmitter located in an air-conditioned room. No ducting is required and the intake air is usually much cleaner than outside air. It places a substantial heat load on the air-conditioner in the summer, but it is a source of heat in the winter. This method is used frequently with the lower power transmitters.

Fig. 52b shows a transmitter located in a wall with a non-air-conditioned room behind it. A large exhaust fan is provided in the ceiling and an adequate air intake opening is provided in an outside wall.

Fig. 52c shows a transmitter located in an air-conditioned room with intake and exhaust air ducts to the outside. An auxiliary blower or fan is normally required to overcome pressure drop in the ducting. The air intake and exhaust openings to the outside should be provided with rain shields, insect screens, and dust filters as dictated by the environment. The location of the air intake and exhaust openings should be arranged so that wind pressure will not impede the air flow.

Air filters should be periodically cleaned or replaced according to the transmitter manufacturer's instructions. This is very important because dust clogged air filters may reduce the cooling air flow enough to cause overheating of some of the components. The probability of component failure increases very rapidly when cooling is insufficient.

Dust should be cleaned from the transmitter by means of a brush and vacuum cleaner or as otherwise recommended by the transmitter manufacturer. Usually weekly cleaning is sufficient.