NEAR EAST UNIVERSITY

Faculty of Engineering

Department of Electrical and Electronic Engineering

RADIO BROADCASTING SYSTEM TECHNOLOGY AND PROBLEMS

Graduation Project
EE- 400

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ABSTRACT

This project will deal with basic properties of "Real World" effects caused by the presence of two or more radio signals of identical frequency, together with their effects on an FM and AM transmeters and receivers. Capture ratio, carrier ratios, and residunal signal strength caused by destructive interference are discussed. The reasons behind frequency locked carriers are reviewed, along with the consequences of non-synchronous signals.

For theoretically perfect reception of any frequency modulated (FM) signal, an infinite transmission and reception bandwidth is required. This is due to the nature of FM, which creates an infinite number of sidebands whose structure is determined by the modulation index. In a perfect FM transmitter, the output power remains constant, but as the modulation index changes, the power distribution between the carrier and the sidebands changes.

Practical applications require finite bandwidth restrictions on the FM signal. For the broadcaster, several elements reduce the transmitted bandwidth of the FM signal, including tuned stages in the transmitter grid and output, and the transmitting antenna itself. The higher order FM sidebands will be slightly attenuated in amplitude and shifted in phase as they pass through the final amplifier stage. These alterations in the sideband structure that are introduced by the amplifier passband, result in distortion after FM demodulation at the receiver. This will cause the amplitude and phase errors to affect both the upper and lower sidebands equally or symetrically.

In this project we are analising the problems of the broadcasting in FM and AM modulations and the alternative methods to solve these problems .

INTRODUCTION

Technical standards in concert with developments in international standards forums, and is working towards the world-wide implementation of a single standard. This will mean that radio sets will be manufactured and marketed world-wide to the same technical standards, enabling any set to plug into the Information Highway.

At present, every country except the United States is moving towards implementation of a wide-band system of digital radio. The Eureka-147 wide-band system has already been accepted as a world standard by the International Telecommunications Union. The Americans are trying to develop a system which would carry digital programming along with the conventional analogue in the AM and FM band. Only the wide-band implementation has the capacity to play a meaningful role in the Information Highway. An endorsement by the Information Highway Council would be helpful to the Task Force in its advocacy of the wide-band radio approach and its world-wide acceptance.

For theoretically perfect reception of any frequency modulated (FM) signal, an infinite transmission and reception bandwidth is required. This is due to the nature of FM, which creates an infinite number of sidebands whose structure is determined by the modulation index. In a perfect FM transmitter, the output power remains constant, but as the modulation index changes, the power distribution between the carrier and the sidebands changes.
Practical applications require finite bandwidth restrictions on the FM signal. For the broadcaster, several elements reduce the transmitted bandwidth of the FM signal, including tuned stages in the transmitter grid and output, and the transmitting antenna itself.

Limited bandwidth RF power amplifiers are widely used in frequency modulation (FM) broadcast transmitters to increase the level of the FM signal at the exciter output to the kilowatt or higher power output levels The power amplifier (PA) is typically a high gain, single-tube, class C, tuned, radio frequency (RF) amplifier The PA design goal is to deliver the authorized power output to the antenna with high efficiency and reliability while providing excellent modulation performance.

This project presents an explanation of synchronous AM noise caused by

FM modulation of limited bandwidth systems. Synchronous AM noise is presently one of the "hottest" topics among FM and TV-Stereo broadcast engineers.

The causes of this type of incidental AM modulation in the presence of FM modulation are reviewed with emphasis on the practical application of synchronous AM noise measurements to optimize transmitter tuning.

The Project will deal with basic properties of "real world" effects caused by the presence of two or more radio signals of identical frequency, together with their effects on an FM receiver. Capture ratio, carrier ratios, and residunl signal strength caused by destructive interference are discussed. The reasons behind frequency locked carriers are reviewed, along with the consequences of non-synchronous signals.

1. SECOND GENERATION TECHNIQUES FOR AM STEREO EXCITER DESIGN

1.1 INTRODUCTION.

With the introduction of AM stereo to the broadcast industry, a new transmission mode has been defined with a new set of complex nnd unique problems to be overcome. Not only are there multiple systems available to transmit stereo due to the FCC marketplace decision, but within each system it is possible to improve the design quality and stereo performance.

During the infancy of AM stereo, there were only the system proponents manufacturing their own equipment. This first generation hardware was not broadcast quality and often fell short in producing the best possible performance for its particular system. Controls for alignment and operation were frequently inaccessible. Today there is a great need for more flexible and reliable hardware. Motorola, Inc., the inventor of the C-QUAM system, has licensed several experi enced broadcast equipment manufacturers to fill this need. This presentation will review some of the improvements and new approaches developed by

1.2 SECOND GENERATION REFINEMENTS.

After reviewing the currently available hardware for AM stereo, several areas for improvement were discovered. Many of these improvements were based on state of the art design techniques employed in the BE FX-30 FM exciter and the BE FS-30 FM Stereo Generator. Others were new innovations developed to improve the C-QUAM system performance. These refinements include:

1. Digital, independent IF modulation technique.
2. Simplified transmitter interfacing.
3. Extended RF output power range.
4. AM SCA capability.
5. Transmitter protection circuitry.
6. Balanced, transformer less audio inputs and outputs.
7. External reference capability to eliminate "platform motlon".

8. Human engineering for easy accessibility.
9. Remote control and status.

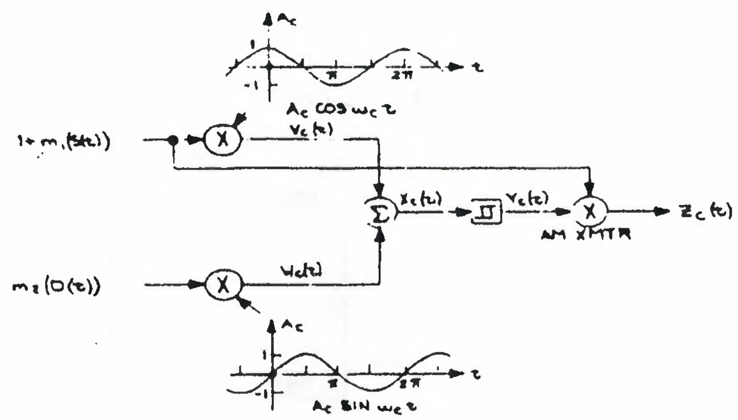
1.3 Digital Independent IF Modulation.

Digital independent IF modulation is the heart of the BE AX-10 AM stereo exciter. All clock signals are derived from a single 10 MHz temperature compensated crystal oscillator (TCXO). This highly stable reference improves overall stability. The stereo signal is generated at an intermediate frequency of 250 kHz for all station frequencies assuring equal stereo performance across the entire AM band. Each audio channel is modulated separately, then summed to L+R and L-R, hence the term independent IF modulation. This scheme provides independent equalization of left and right channels for best separatlon, distortion and frequency response. The total system provides a stable carrier frequency output across the AM band without successive retuning or nulling, and with repeatable stereo performance at all frequencies.

Figure 1.1 shows the conventiunal matrix modulation approach to C-QUAM stereo generation. The summed L+R information, together with a DC offset to produce a carrier [1+M, (S(t))] is modulated with a Ø degree RF signal (Ac (COS W_ct)]. The difference L-R information [M2(D(t))] is modulated with an RF signal phase shifted by 90 degrees [Ac (SIN W_ct)). These two signals are summed, providing a quadrature modulation signal (Xc(t)]. At this point, stereo information is fully present and can be decoded by a synchronous detector. However, this signal is not mono compatible on an envelope detector. Therefore, it is amplitude limited to produce a quadrature phase-only signal [Yc(t)]. This phase modulated RF signal is then amplitude modulated with the 1+M, (S(t)) signal in the AM transmitter to produce the mono compatible C-QUAM signal (Zc(t)].

Figure 1.2 describes a fully independent modulation C-QUAM stereo system developed by Broadcast Electronics. In this configuration, the left channel

[M3(L(t))] is modulated with a 90 degree phase referenced RF signal [Ac (SIN GJ ct)) to produce Qc(t).



I. $V_c(t) = [\,1 + M_1\,(\,S(t)\,)\,]\,A_c\,\cos\omega_c t$ (a)

$W_c(t) = M_2\,(\,D(t)\,)\,A_c\,\sin\omega_c t$ (b)

Where $M_1\,(\,S(t)\,)$ and $M_2\,(\,D(t)\,)$ are the sum and difference modulatine components respectively.

II. $X_c(t) = A_c\,[[\,1 + M_1\,(\,S(t)\,)\,]\,\cos\omega_c t + M_2\,(\,D(t)\,)\,\sin\omega_c t\,]$

$= A_c\sqrt{[\,1 + M_1\,(\,S(t)\,)\,]^2 + M_2\,(\,D(t)\,)^2}\;\cos(\,\omega_c t + \theta\,)$

Where $\theta = \tan^{-1}\left[\dfrac{M_2\,(\,D(t)\,)}{1 + M_1\,(\,S(t)\,)}\right]$

$X_c(t)$ Represents Quadrature Modulation

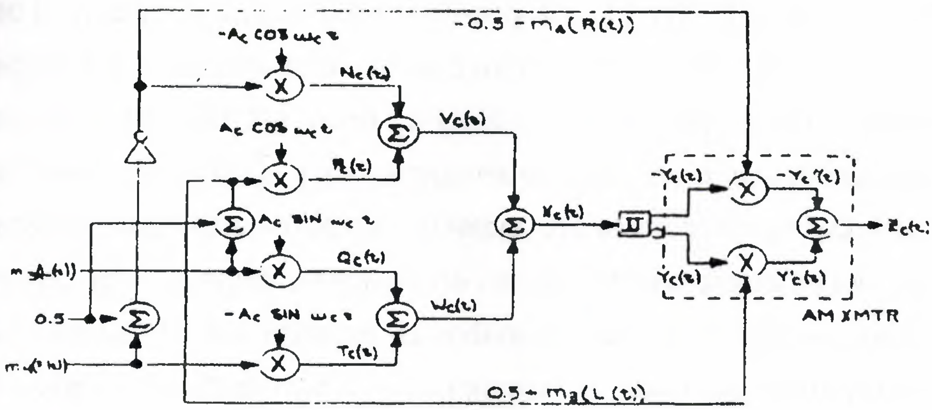
III. $Y_c(t) = A_c\,\cos(\,\omega_c t + \theta\,)$ (Quadrature Phase Information Only)

IV. $Z_c(t) = A_c\,[\,1 + M_1\,(\,S(t)\,)\,]\,\cos(\,\omega_c t + \theta\,)$

$Z_c(t)$ Represents C-QUAM Modulation

FIGURE 1.1 CONVENTIONAL MATRIX C-QUAM STEREO GENERATION

The right channel [M4(R(t))] is modulated with a 270 degree phase referenced RF signal [-Ac (SIN W_ct)] to produce Tc(t). These two signals are summed to produce Wc(t). M3(L(t)) is also summed with a OC offset to produce a carrier signal of half-magnitude, then modulated with a degree phase referenced RF signal [Ac (COS W_ot)) to produce Pc(t). M4(R(t)) is sumned with a DC offset of half-magnitude, inverted, then modulated with a 180 degree phase referenced RF signal [-Ac (COS W_ot)] to produce N_o(t). These signals are summed to produce Y_o(t).Y_c(t) and W_c(t) are summed to produce the identical quadrature modulation as in Figure 1 [X_c(t)). This signal is amplitude limited producing two quadrature phase-only Rf signals 180 degrees out-of-phase (Y_c(t) and -Y_c(t)]. These RF signals are amplitude modulated independently by left channel plus half carrier [0.5+M3(L(t))) producing $Y_c(t)$ and -right channel plus -half carrier [-0.5-M4(R(t))] producing $-Y_c(t)$. These signals are sumned to produce the identical C-QUAM signal $(Z_c(t)]$.



V. $N_c(t) = [\,-0.5 - M_4(\,R(t)\,)\,]\,[\,-A_c \cos \omega_c t\,]$

$P_c(t) = [\,0.5 + M_3(\,L(t)\,)\,]\,[\,A_c \cos \omega_c t\,]$

Where $M_3\,L(t) = \dfrac{M_1(\,S(t)) + M_2(\,D(t)\,)}{2}$, $M_4\,R(t) = \dfrac{M_1(\,S(t)\,) - M_2(\,D(t)\,)}{2}$

$V_c(t) = N_c(t) + P_c(t)$

$= [\,1 + M_3(\,L(t)\,) + M_4(\,R(t)\,)\,]\,A_c \cos \omega_c t$ Equivalent to I(a)

VI. $Q_c(t) = M_3(\,L(t)\,)\,A_c \sin \omega_c t$

$T_c(t) = M_4(\,R(t)\,)\,-A_c \sin \omega_c t$

$W_c(t) = Q_c(t) + T_c(t)$

$= [\,M_3(\,L(t)\,) - M_4(\,R(t)\,)\,]\,A_c \sin \omega_c t$ Equivalent to I(b)

VII. $-Y_c'(t) = 0.5\,A_c \cos(\,\omega_c t + \theta\,) + M_4(\,R(t)\,)\,A_c \cos \omega_c t + \theta\,)$

$Y_c'(t) = 0.5\,A_c \cos(\,\omega_c t + \theta\,) + M_3(\,L(t)\,)\,A_c \cos \omega_c t + \theta\,)$

VIII. $Z_c(t) = -Y_c'(t) + Y_c'(t)$

$= A_c\,[\,1 + M_3(\,L(t)\,) + M_4(\,R(t)\,)\,]\cos(\omega_c t + \theta)$

Which is equivalent to IV.

Figure 1.2 Independent modulation C-QUAM.

In this configuration, the left channel (M3(L(t))] is modulated with a 90 degree phase referenced RF signal [Ac (SIN G ct)] to produce Qc(t).The right channel [M4(R(t))] is modulated with a 270 degree phase referenced RF signal [-Ac (SIN W_ct)] to produce $T_c(t)$. These signals are summed to produce $W_c(t)$. M3(L(t)) is also summed with a DC offset to produce a carrier signal of half-magnitude, then modulated with a degree phase referenced RF signal [Ac (COS W_ct)] to produce Pc(t). M4(R(t)) is summed with a DC offset of halfmagnitude, in.verted, and modulated with a 180 degree phase referenced RF signal [-Ac (COS W_ct)] to produce Nc(t). These signals are summed to produce $V_c(t)$.$V_c(t)$ and $W_c(t)$ are summed to produce the identical quadrature modulation as shown in Figure 1.1 and Figure 1.2 ($X_c(t)$)].

From this point, the system is identical to that of Figure 1.1. It is amplitude limited to produce a quadrature phase-only signal [Yc(t)]. This phase modulated RF signal is then amplitude modulated with the 1+M,(S(t)) signal in the AM transmitter to produce the mono compatible C-QUAM signal [$Z_c(t)$)]. While the end result in the transmitter is a matrix type modulation, the phase modulated RF signal is derived through independent modulators, thereby providing much less i teraction of left and right channels. Although the derivations and diagrams for the fully independent and the modified independent modulation techniques appear much more complex than their matrixed counterpart, in reality the circuitry remains virtually the same.

1.4 Transmitter Interfacing Requirements.

In any AM stereo system employing some form of phase modulated Rf signal combined with conventional audio amplitude modulation of that signal, equalization must be used in the phase modulated signal and/or the mono audio signal to the transmitter. This is necessary to match the time delay characteristics of the two paths to construct the proper C-QUAM sideband distribution at the transmitter output, there by insuring correct de-matrixing to left and right channels in the receiver. Figure 1.3 shows the relationship of amplitude and phase matching required between the mono L+R signal and the phase modulated L-R signal to a-chieve any given separation when de-matrixed.

Due to the wide variety of AM transmitters in use today, the task of equalizing these paths to transmit accurate stereo becomes complex. Equalization re-quirements differ greatly from one transmjtter to another, but in most cases the required equalization can be divided into three sections:

1. Group delay in either the RF or transmitter audio path to match the pro-pagation differences between the two.

2. Some form of phase and amplitude correction for higher frequencies due to transmitter and antenna bandwidth/phase characteristics.

3. Low frequency phase correction in some cases.

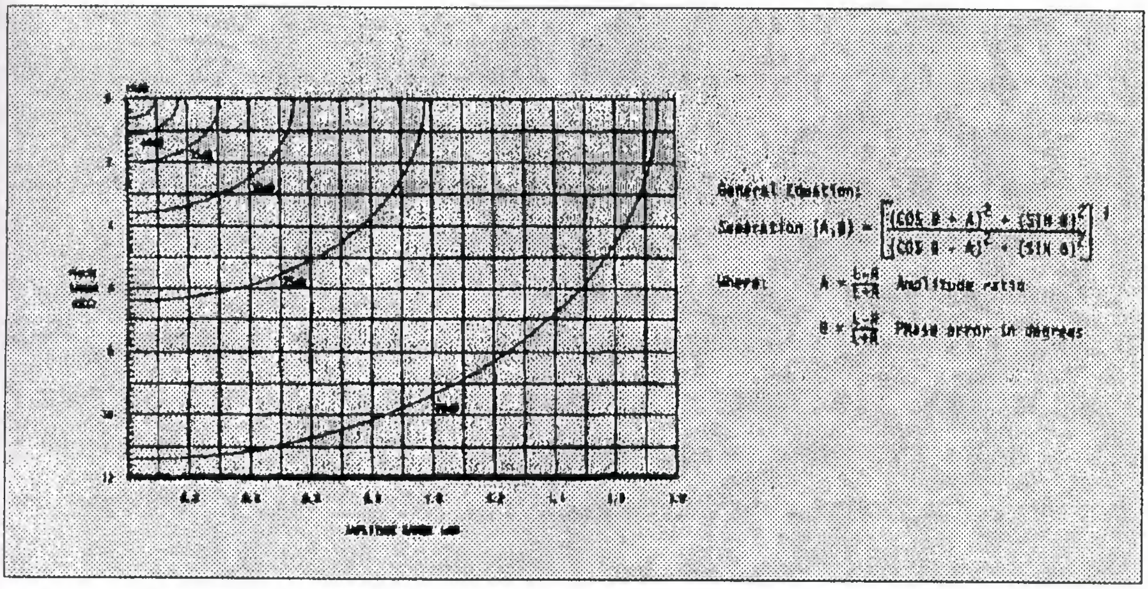


FIGURE 1.3. STEREO SEPARATION AS A FUNCTiON OF AMPLITUDE AND PHASE RESPONSE

Determining the exact requirements for a particular transmitter can be a confusing task, and often a series of trial-and-error experimentation results. This process involvestrying various equalizers in the RF and audio paths, thereby testing their effect on stereo seperation and distortion. Until specific transmitter equalization requirements are documented, alignment will prove to be an involved undertaking. Because of the need to route any or all of the equalization circuits to either the RF or transmitter audio paths, some form of "patch bay" setup would be advantageous for block equalization selection. This patch bay approach is accomplished by miniature matrix switches accessible under the top cover . Once the basic layout of the switch is understood, it becomes extremely fast and easy to select any equalization and to route its output to either the input of another equalization block, or directly to the required path.

The type and amount of available equalization varies from exciter to exciter, but in general it can be said the greater the available range of equalization, the more transmitters can be easily converted to transmit AM stereo.

As an example of one set of equalization, the next few paragraphs will discuss in detail the equalization circuitry used exciter. The amount of available equalization was chosen after researching AM stereo consultants and users. Two identical and independent sets of equalization are provided for day and night correction of changing antenna patterns, low power setting, or for a standby transmitter. Day/night equalization selection and status are remote controllable with either momentary ground closure, or by constant ground closure which may be initiated by antenna selection. It was found that some AM stereo exciters did not contain enough available group delay. Systems may require more than 40 microseconds of delay. For that reason, any amount of constant group delay from Ø to 66 microseconds can be selected. This is accomplished by a miniature rotary switch selecting coarse delay in 4 microsecond increments followed by a Ø -6 microsecond fine delay adjustment . In addition, by routing day equalization through night equalization via the matrix switching, a single equalization of Ø -132 microseconds of group delay is possible. So far, only the solid state transmitter has required more than 60 microseconds. This installation required over 100 microseconds of group delay equalization. The amplitude response remains constant in this equalizer from 20-20,000 Hz. due to the difterent phase and ampl·tuoe responses of the RF and transmitter audio chain at higher frequencies, correction must be made to provide good separation and distortion. Some typical responses used to equalize the system at high :odulating frequencies. Because of the separate turnover and peaking available, the responses can be tailored to fit the particular installation. Another interfacing requirement for the exciter is the available range of RF output power. It is generally better to inject the RF signal as far as possible into the transmitter to diminish the effect of bandpass or lowpass filters in low level stages. These filters will degrade overall stereo performance and must be corrected with equalization circuitry in the exciter. By providing 150 milliwatts to 10 watts RMS, a suitable insertion point should be found for good stereo performance. 150 milliwatts into 50 Ohms corresponds to standard TTL signal level to drive transmitters with digital inputs. Some digital transmitters require an asymmetrical duty cycle square wave for best performance. In this case, an optional TTL interface provides from 25% to 75% continuously adjustable duty cycle.

In an effort to remove any phase and amplitude mismatches between the RF and transmitter audio chain due to audio transformers, the mono envelope signal from the exciter is actively balanced. A high output level of +20 dBm provides additional headroom and permits the use of lossy modulation enhancement devices. This output is continuously variable to accommodate transmitters with different input level requirements and more importantly, to exactly match corresponding L+R to I-R levels for good separation and crosstalk. For those transmitters requiring different daytime and nighttime audio levels, separate output level adjustments are included.

1.5 AM SCA.

With the recent FCC deregulation of AM SCA, AM stations are now able to use subsonic phase modulation for services such as load management. For conventional mono AM stations, this requires additional equipment. For AM stereo stations, however, the addition of AM SCA can be extremely simple.

Figure 1.4 shows the block diagram for the AX-10 pilot tone and AM SCA insertion method. The information to be phase modulated as AM SCA is inserted via the rear panel "Auxiliary Pilot Input". This signal is lowpass filtered to insure higher frequency components are not transmitted, then sumned with the digitally derived and filtered 25 Hz pilot tone. This signal is then sumned differentially with the left [M3(L(t))] and right [M4(R(t))] channel information for modulation .

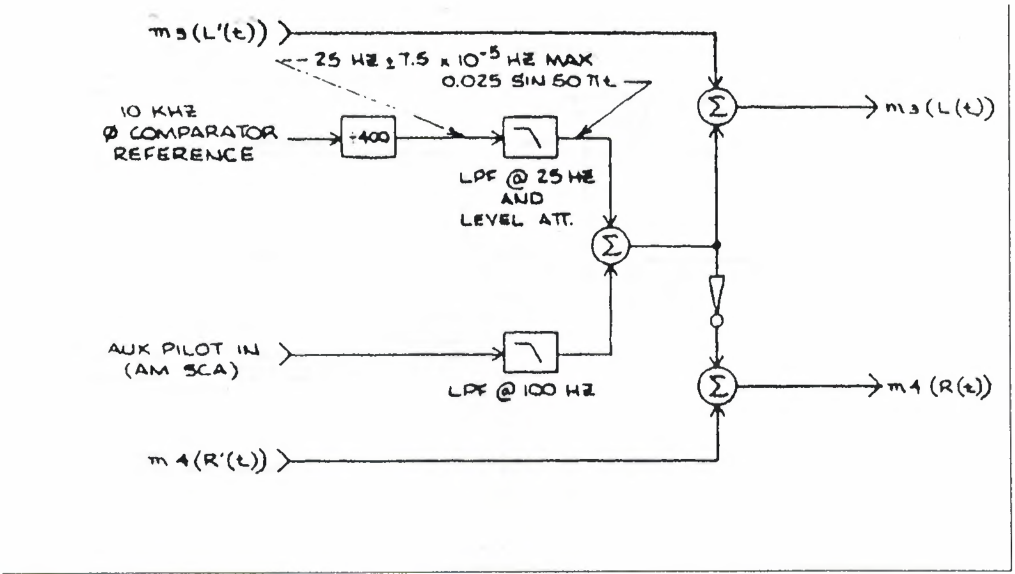


FIGURE 1.4. PILOT TONE AND AM SCA INSERTION CIRCUITRY

1.6 Transmitter Protection.

In any transmission system using a frequency synthesizer to derive individual station frequencies, some form of muting signal should be included during initial lockup time, or if phase lock is lost during normal operation. For safety reasons, a muting signal must be available if the exciter fails to output RF to the transmitter. Some transmitters can be seriously damaged if RF drive is lost. Figure 1.5 details the transmitter protection circuitry in the AX-10 exciter.If the synthesizer loses phase lock or if a loss of RF presence is detected at the output, an external open collector mute signal is initiated to drive a 40 mA ground closure. This signal could be used to remove high voltage to protect the transmitter. Internal to the AX-10, the mute signal will extinguish the day or night LED on the front panel as a local indication.

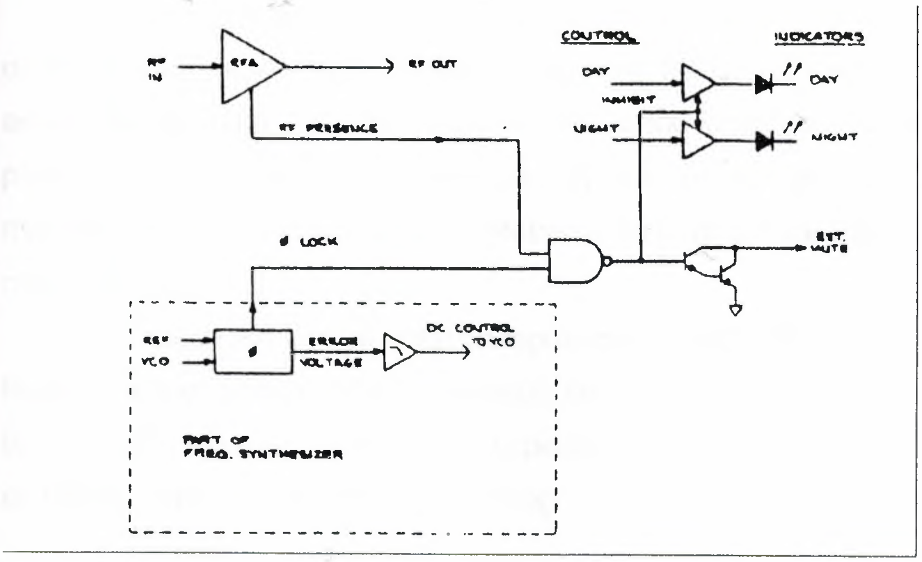


FIGURE 1.5. B.E. AX-10 PHASE LOCK AND RF PRESENCE PROTECTION CIRCUITRY

1.7 Audio Circuitry.

The audio inputs of an exciter should be completely transparent to the applied program content. Some desired characteristics include:

1. Actively balanced Inputs.

2. High comnon mode rejection ratio (CMRR).

3. Good transient response.

4. Low distortion and noise.

5. Flat frequency response from 1 Hz to 15 kHz.

6. Identical phase and amplitude characteristics for both inputs.

Transformers are capable of balanced input, CMRR and acceptable noise and distortion, but are lacking in transient response, frequency response, phase and amplitude matching of inputs. Incorrect phase and amplitude matching will result in poor main-to-sub and sub-to-main crosstalk, just as poor amplitude and phase matching of main and sub channel response throughout the transmitter results in poor separation.

Fully balanced instrumentation inputs are capable of frequency response from DC to well above 15 kHz, distortion below 0.005%, signal to noise of greater than 100 dB, excellent CMRR, and superior transient response. They also provide excellent phase and amplitude matching.

1.7 External Reference Capability.

For AM stereo systems employing phase modulation, nighttime co-channel interference known as "platform motion" can occur under some conditions. While this phenomenon occurs only in fringe areas where even mono reception is poor, there has been some concern about its presence. Platform motion is caused by co-channel stations having a slightly different station frequency due to the timebase employed. In AM stereo, a rotational effect is created as the receiver decodes the frequency difference from one channel to another at a rate equal to the difference in frequency of the co-channel stations. Because the AX-10 is a digital modulation system deriving all station frequencies from one 10 MHz source, the master oscillator can be replaced with a reference source from WWV or some other standard. If all co-channel stations become frequency locked, platform motion is eliminated. The 10 MHz is first divided by 2 to obtain 5 MHz. This is used in two places. First, it is divided by 20 to obtain a 4 phase clock generator at 250 kHz to drive the IF C-QUAM modulator. After stereo generation, the 250 kHz signal is mixed with the second 5 MHz signal, thereby up-converting to 5.25 MHz. This second IF frequency passes through a linear phase bandpass filter to remove other mixing products.

Phase from the 250 kHz clock generator is divided to 10 kHz to provide a reference frequency for the synthesizer. This synthesizer operates from 5.780 MHz to 6.8l0 MHz. This frequency is mixed with the second IF frequency of 5.25 MHz to produce a difference frequency from 530 kHz to 1620 kHz which is lowpass filtered to remove higher order mixing products. The up-down conversion scheme provides a frequency agile system without retuning and elimlnates the need for individual bandpass filters assigned to the station's carrier frequency. The difference term from the last mixer is free of images in the AM band. Since there are no bandpass filters or other tuning adjustments specific to the station frequency, the AX-10 can be quickly moved to any channel assignment by simply reprogranming the frequency synthesizer. This technique also guarantees identical stereo performance across the AM band. Because the synthesizer is phase locked to the master clock and high side injection is used in the last mixer , the frequency errors due to crystal drift subtract, thereby increasing frequency stability. This provides a total error of no more than 5 Hz at carrier frequency across the entire AM band over the Ø -50 degree crating of the TCXO.

1.8 Human Engineering.

Due to the need for flexible interfacing capabilities, any AM stereo exciter must contain a wide range of adjustments from audio, RF and pilot levels to transmitter equalization controls. Accessibility to these controls is of prime importance to the engineer who must align and maintain the exciter. It would be most advantageous for these controls to be available without removal of the unit.

Not all adjustments require immediate access, however there are some which need to be readily available. These include:

1. Transmitter equalization controls (day/night).

2. Transmitter audio level (day/night).

3. RF output level control.

4. Pilot injection level.

Beyond these, any user helpful controls such as mode selection, pilot off switch, single channel limiter defeat switch, manual day/night equalization selection switch, or any required monitoring or diagnostic ports should also be located on the front panel. Should access to internal circuitry be required, the exciter is mounted on standard 19" slide rails for convenience. The top cover can be easily removed. Care must be taken to insure good RFI shielding for AM, FM, and TV frequencies.

1.9 <u>Remote Control and Status Indication.</u>

Under no circumstance should there be any loss in mono loudness to the mono listener during a stereo broadcast, and in fact under normal operating conditions there is not. It is possible, however, to lose up to 6 dB of mono loudness if one audio input to the stereo exciter is lost. For this reason, some form of alternate mode selection should be used. The exciter should be capable of single channel operation with no loss in mono
loudness. The BE AX-10 can be run in one of four modes:

1. Mono Left
2. Mono Right
3. Mono l+R
4. Stereo

If one channel to the exciter should fail, the unit can be switched to the opposite channel with no loss in mono loudness. In all mono modes, the 25 Hz pilot tone is muted to return the C-QUAM only receivers to their mono state. Because of this, the exciter can be run in the Mono L+R mode during long mono transmissions.

All modes and equalization states are remote selectable with momentary ground closures. Their status indications are also provided. The transmitter mute signal is also provided on the same connector. All remote controls and indications are optically isolated to reduce ground loops and RF contamination. The inclusion of a standard remote system removes the need to add additional interfacing equipment in the field. It also speeds changeover time to mono modes in case of failure.

2.OPTIMUM BANDWIDTH FOR FM TRANSMISSION

2.1INTRODUCTION

For theoretically perfect reception of any frequency modulated (FM) signal, an infinite transmission and reception bandwidth is required. This is due to the nature of FM, which creates an infinite number of sidebands whose structure is determined by the modulation index. In a perfect FM transmitter, the output power remains constant, but as the modulation index changes, the power distribution between the carrier and the sidebands changes.

Practical applications require finite bandwidth restrictions on the FM signal. For the broadcaster, several elements reduce the transmitted bandwidth of the FM signal, including tuned stages in the transmitter grid and output, and the transmitting antenna itself.

For the receiver, the desired signal must be selected, while all others are rejected. This is done primarily by the intermediate frequency (IF) filter. This IF filter is by far the largest contributor to the total RF bandwidth limitation, typically being less than 300 kHz wide (3 dB). Some receivers are available with selectable IF bandwidths of 1 MHz or more. As receiver technology advances, this typical IF bandwidth of less than 300 kHz may very well increase. In any case, broadcasters should not allow receiver shortcomings to limit their efforts to transmit the best possible RF signal.

There is a wide diversity of opinion among both broadcasters and broadcast equipment manufacturers as to the required RF bandwidth for quality FM transmission. At first glance, the "more is better" assumption is likely to prevail. But a closer look reveals some practical considerations which show a need to limit the transmission bandwidth to reduce other problems, especially the ever increasing potential for RF intermodulation in broadcast transmitters.

Therefore, the purpose of this chapter is to determine how much bandwidth is required for low distortion FM transmission, and at what bandwidth the point of diminished returns regarding distortion improvement is reached.

2.2 Bandwidth Limitations

Several factors contribute to limit the transmitted RF bandwidth of an FM transmission facility. Often, the limiting factor is the antenna system itsef . For community tower applications, wideband panel antennas are available. In this case, the hybrid combiners and cavity tuned filters are predominantly the narrowest elements in the transmission path.

The transmitter also plays a role in the total RF bandwidth of station. Several key areas determine the bnndwidth limitations of a transmitter.

Asolid state broadcast transmitter is rarely the limiting factor for RF bandwidth. It should be much wider than the antenna, combiners or cavity tuned filters. For tube transmitters the story is much more complex. The output of a high power tube transmitter consists of a frequency selective network in the form of a tuned cavity. The bandwidth of the cavity depends on its construction, the amount of tube output capacitance, and how heavily it is loaded.

The output (cavity) bandwidth is often considered the limiting factor for the whole transmitter. Oddly enough, this is not the case for the grid driven amplifier The large grid input capacitance of a power vacuum tube causes the loaded Q of the grid circuit to be even higher than the output . This fact is often ignored because the grid is driven into saturation which partially masks the amplitude variations of the grid matching network. The popular method of measuring transmitter bandwidth with a network analyzer is somewhat misleading, since the measured 3 dB amplitude bandwidth does not completely account for the grid circuit effects due to saturation. The non-linear response of the power tube further effects the response, especially close to the carrier frequency. This is why accurate predictions of the transmitter 3 dB bandwidth cannot be made by looking at synchronous AM performance, or visa-versa. The amplitude response of the transmitter can be made flatter over a ±75 kHz deviation from carrier due to heavy saturation, heavy loading, and tube impedance non-linearity . Measuring this "0.1 dB" bandwidth (-45 dB synchronous AM) proves to be inaccurate when attempting to predict the 3 dB bandwidth from this information. For a properly adjusted transmitter, the synchronous AM performance tends to predict a wider than actual 3 dB bandwidth.

Audio performance is also not completely predictable from a measured transmitter amplitude response. The problem arises from the group delay variations (phase response) of the grid circuit and the non-linear nature of the final tube, which can have serious effects on the distortion performance of the entire transmitter. Group delay variations degrade the composite amplitude response, which in turn limits stereo separation. A properly designed, broadband grid matching network is essential for proper operation of the entire transmitter. Even if the output bandwidth were not limited, the grid circuit could seriously affect the transmitter's performance.

This degradation due to phase response is true for any tuned cir- cuit, even if that stage is run into saturation. Therefore it makes sense to eliminate as many tuned stages as possible. This is why a wideband, solid state exciter and intermediate power amplifier (IPA) are advantageous i,n high power FM transmitters, even though the output stage uses a tube .

2.3 WHY LIMIT BANDWIDTH?

If there were only one radio signal being transmitted at any given time, there would be no need to limit the bandwidth. However, any time two signals are present, there exists the possibility of RF intermodulation between them. Al1 that is required is a non-linear device acting as a mixer, which creates two more intermodul·ation products. The transmitter final amplifier is that non-linear active device. If any other frequency finds its way back into the output stage, RF intermodulation will occur. This mixing will have some conversion loss, referred to as "turn-around-loss". There are three main contributors to the total turnaround-loss . They are:

I. The in-band conversion loss of the non-linear device.

2.The attenuation of the interfering signal due to the selectivity of the output stage.

3.The attenuation of the resulting IM products due to the selectivity of the output stage.

This will be a design trade-off between system modulation performance and immunity from RF intermodulation. It is important to note that the broadband nature of a solid state broadcast transmitter makes its susceptibility to RF intermodulation greater than a tube/cavity output stage.

2.4TESTING RF BANDWIDTH PERFORMANCE

How is the optimum bandwidth determined? There are models available to predict distortion performance, but these require that the transfer function of the network is known and assumed to be passive. It , is practically impossible to model an FM broadcast transmitter operating class C, due to its nonlinear transfer function.

Astraightforward empirical alternative is to measure the performance degradation of a "perfect" modulator when it is passed through a passive band limiting network. A real broadcast transmitter is not practical for this test, as there is only a very limited range of bandwidth variation available, and determining its true bandwidth is difficult due to grid saturation effects.

A test cavity was constructed to simulate the effects of band limiting. The tuning and loading range was sufficient to allow bandwidth testing from 400 kHz to 3 MHz (-3 dB). While the effects of the grid circuit were not seen, the output bandwidth effects were very accurately modeled. This was useful for several reasons. First, it showed the performance degradation caused by various bandwidth limitations. Second, it shows at what bandwidth performance ceased to improve. Third, it provides a good basis to compare to a real broadcast transmitter. Figure 1 shows the physical construction of this test cavity.

The resulting data gives a clearer insight into the effects of the grid circuit and the non-linear effects of the output tube, based on actual performance vs. measured bandwidth of a real transmitter. It also shows that 3 dB bandwidth is not necessarily a good measure of synchronous AM performance due to the more complex response of the entire transmitter design.

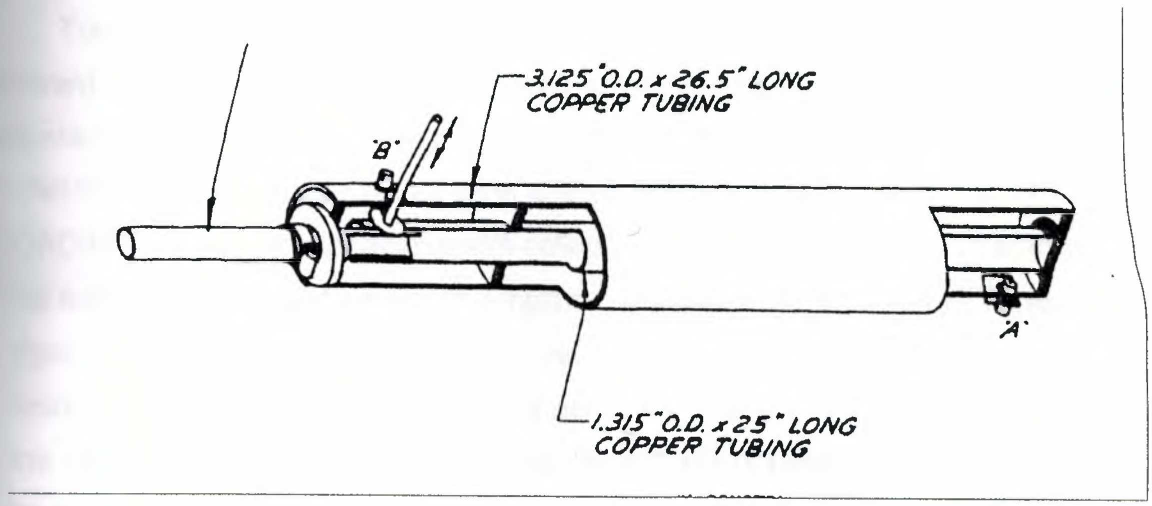


FIGURE 2.1. TEST CAVITY CONSTRUCTION

2.5 The Test Equipment

Before a determination of performance degradation can be made, a benchmark must,exist to define the desired goal, or "perfect" FM modulation. In a wideband RF environment, the system performance is limited only by the FM exciter used (the modulator), and the receiver (demodulator). The accuracy of the test is limited by the distortion, noise, and composite amplitude response of this test equipment.

This combination provided a guaranteed signal to noise ratio of -90 dB minimum, performance better than 0.005%, composite amplitude response of better than f0.025 dB, composite phase response of ±0.1 degree, and stereo separation of 60 dB, 30 Hz to 5 kHz, greater than 52 dB, 5 kHz to 15 kHz.

3. FINE TUNING FM FINAL STAGES

3.1WHY IS CORRECT TUNING IMPORTANT?

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

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

3.2FM MODULATION THEORY

3.2.1FM SIDEBAND STRUCTURE

The frequency modulated Rf output spectrum contains many sideband frequency canponents, theoretically an infinite number. They consist of pairs of sidebands spaced from the carrier frequency by multiples of the modulating frequency. When the modulation index is small (M=0.5) the amplitude of the second and higher order sidebands is small so that the output consists mainly of the carrier and the pair of first-order sidebands, as illustrated in Figure3.IA. The total transmitter RF output power remains constant with modulation, but the distribution of that power into the sidebands varies with the modulation index so that powg r at the carrier frequency is reduced by the amount of power added to the sidebands.

Figures 3.1B and 3.1C illustrate the frequency components present for modulation indices of 5 and of 15. Note that the number of significant sideband components becomes very large with a high modulation index. The total bandwidth occupied extends beyond 75 kHz from the carrier depending upon the modulating frequency. This single tone m dulating frequency analysis is useful in understanding the general nature of FM and for making tests and measurements. When program modulation is applied, there are many more sideband components present and they are varying so much that sideband energy becomes distributed over the entire occupied bandwidth ratf.er than appearing at discrete frequencies.

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

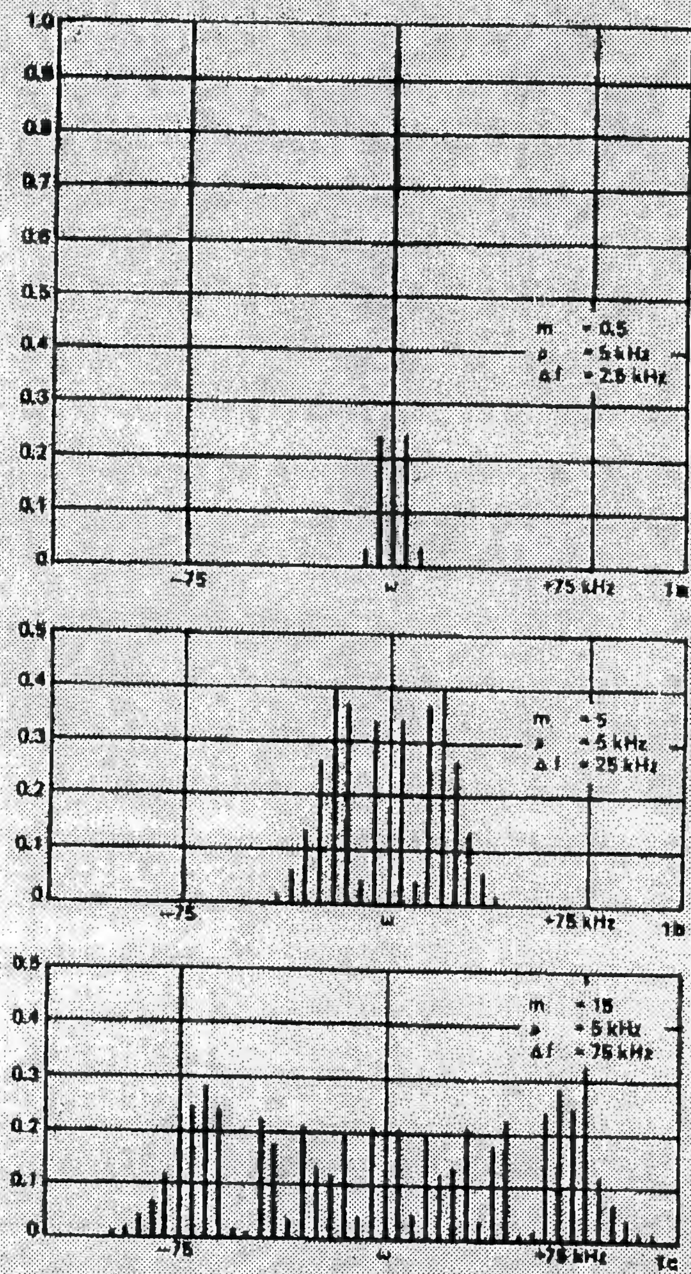


Figure 3.1 RF Spectrum with modulation ındices of 0.5, 5 and 15

3.2.2 HOW DOES TUNING AFFECT THE FM SIDEBAND,S

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

3.3 TWO TYPES OF AM MODULATION

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

1. Asynchronous AM modulation is measured without FM modulation and is primarily related to power supply ripple.
2. Synchronous AM modulation (incidental AM) measured with FM modulation is related to the tuning and overall bandwidth of the system.

3.3.1 ASYNCHRONOUS AM

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

3.3.2 SYNCNRONOUS AM

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

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

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

3.4 WHY IS SYNCHRONOUS AM IMPORTANT?

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

3.4.1 HOW G00D SHOULD SYNCHRONOUS AM BE?

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

PEAK TO PEAK SYNCHRONOUS AM (below equivalent 100% AM) (with t75 kHz @ 400 Hz FM)	APPROXIMATE BANOWIOTH (-3dB)
-40dB	I.IMHz
-45d8	I.4MHz
-50d8	2.OMHz
-55d8	2.5MHz
-60d8	3.4MHz

3.5 TUNING YOUR TRANSMITTER FOR PEAK PERFORMANCE

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

3.5.1 INITIAL TUNING AND LOAOING

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

3.5.2 INPUT TUNING AND MATCHING

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

3.5.3 OUTPUT TUNING

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

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

3.5.4 OUTPUT LOADING

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

3.6 AUTOMATIC POWER CONTROI HEADROOM

Automatic power control (APC) feedback systems are utilized in many transmitters to regulate the power output around a predetermined setpoint with variations in AC line voltage or changes in other operating parameters. Most modern FM broadcast transmitters utilize.a single high gain tetrode as the final amplifier stage with adjustment of the screen voltage providing fine adjustment of the output power. For each power output level there is one unique combination of 5creen voltage and output loading that will provide peak operating efficiency. If the screen voltage is raised above this point without a corresponding increase in loading, there will be no further increase in power output with rising screen voltage and screen current. If the screen voltage is raised without sufficient loading, a screen current overload will occur before the upward adjustment in power output is obtained.

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

3.7 MINIMIZING SYNCHRONOUS AM

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

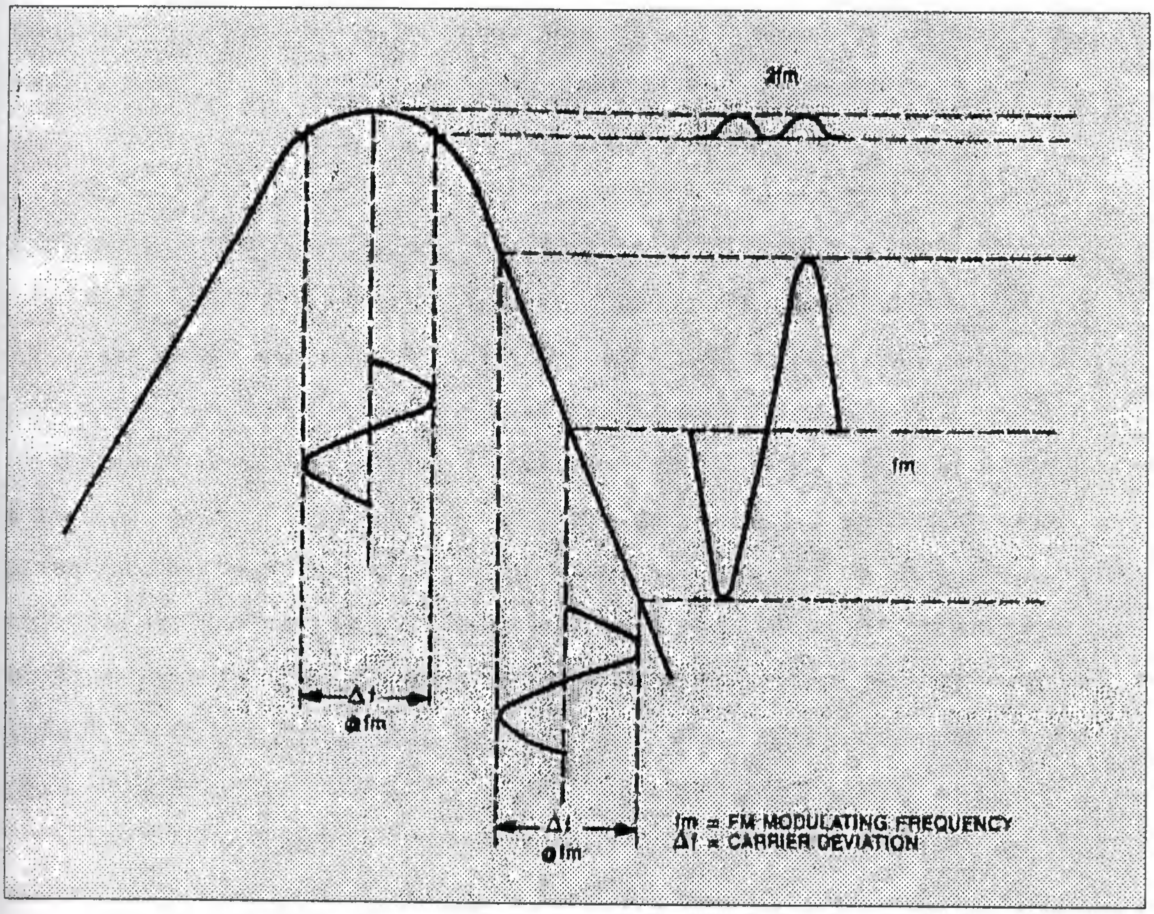


FIGURE 3.2. SYNCHRONOUS AM WAVEFORMS

3.8 THE NEED FOR A PRECISION ENVELOPE DETECTOR

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

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

3.9 MINIMUM SYNCHRONOUS AM VERSUS EFFICIENCY

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

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

3.10 FINE TUNING TO MINIMIZE CROSSTALK INTO THE SCA

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

3.10.1 COMPOSITE BASEBAND SPECTRUM ANALYSIS

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

3.10.2 TUNING SENSITIVITIES

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

3.11 TEST EQUIPMENT SETUP

Figure-3.3 illustrates a typical test equipment setup and shows a block diagraa of the required test equipment for making both synchronous AM nnd composite waveform aeasurements. A low frequency (10 Hz to 200 kHz) spectrum analyzer is used to determine the nmount and location of distortion products added to the baseband signal as it passes through each stage of the overall system.

Note that the composite baseband can be checked at various points along the transmission path in order to verify the perforaiance and distortion contribution of each subsystem. The modulation monitor or modulation analyzer used to demodulate the RF to composite baseband must have a highly linear pulse counting dis riminator in order to avoid the introduction of distortion products during the demodulation process.

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

4. THE SIGNIFICANCE OF RF POWER AMPLIFIER CIRCUIT TOPOLOGY ON FM MODUIATION PERFORMANCE

4.1 INTRODUCTION

Limited bandwidth RF power amplifiers are widely used in frequency modulation (FM) broadcast transmitters to increase the level of the FM signal at the exciter output to the kilowatt or higher power output levels The power amplifier (PA) is typically a high gain, single-tube, class C, tuned, radio frequency (RF) amplifier The PA design goal is to deliver the authorized power output to the antenna with high efficiency and reliability while providing excellent modulation performance.

This chapter discusses various topologies of the input and output circuits of a vacuum tube RF power amplifier and analyzes their effects on the transmitter bandwidth. Results of computer circuit analysis and actual measured bandwidth data of two different topologies are compared. Design considerations for high quality transmitter performance and desired level of transparency to a wideband FM broadcast signal is discussed including the effects of RF power amplifier tuning on the FM modulation performance. The contents of the paper is divided into the following main headings:

1. Frequency Modulated Signal And Effects Of Bandwidth Limitation On The Transmitter Performance.
2. RF Power Amplifier Design Considerations
   - Primary Design Factors.
   - Input Circuit Configurations And Their Effects On The Transmitter Amplitude And Group Delay Responses.
   - Output Circuit Conflgurations And Their Effects On The Transmitter Amplitude And Group Delay Responses.
   - Computed/Measured Amplitude And Group Delay Responses.
3. Modulation Performance Of A Typical 20 kW Single-Tube FM Transmitter.
4. Effects Of Power Amplifier Tuning On FM Modulation Performance.

4.2 FRE QUENCY MODULATED SIGNAL AND EFFECTS OF BANDWİDTH LIMITATION ON THE TRANSMETTER PERFORMANCE

4.2.1 Frequency Modulated Signal

A Frequency Modulated RF Signal with modulation index "m", carrier frequency "f_c", and single-tone modulation frequency "f_m" can be represented by the following mathematical expression .

$$E(t) = E_c \cdot Cos[(w_c \cdot t + m \cdot Sin(w_m \cdot t)],$$

Where:

E_c = The unmodulated carrier amplitude constant $W_c = 2\pi \cdot f_c$ (carrier frequency)

$w_m = 2\ \pi f_m$ (modulating frequency)

$m = \Delta f/f_m$ = frequency deviation/modulating frequency

In an FM si nal, the deviation 'Δf' of the instantaneous frequency from the average or the carrier frequency) is directly proportional to the instantaneous amplitude of the modulating signal. The rate of frequency deviation is the modulating signal frequency.

The above FM Signal can be expressed as an infinite series of discrete spectral components using trigonometric expansions and series representations of Bessel functions .

$$E(t) = E_c \cdot \ \Sigma \sum_{n=-\infty}^{\infty} J_n(m) \cdot Cos[(w_c + n \cdot w_m) \cdot t]$$

Where $J_n(m)$ are Bessel functions of the first kind and n^{th} order with argument "m". The numeric values of the Bessel functions $J_n(m)$ for different "n" express the amplitudes of the various frequency components relative to the unmodulated carrier amplitude. The values of $J_n(m)$ depend on the argument "m" and the order "n". These can be found from the mathematical tables.

4.2.2 Occupied Signal Bandwidth

Occupied Signal Bandwidth "BW" of an FM signal can be calculated for a single tone modulation by the following formula:

$BW = 2 \cdot n \cdot f_m$.

Where "n" is the number of significant sideband components which depends on the value of $J_n(m)$ and changes with the modulation index "m".

"f_m" is the modulating frequency.

The value of "n" can be accurately found from the mathematical tables by ignoring sideband components with amplitudes $J_n(m)$ less than a certain desired number. The maximum value of "n" which need be considered for a given "m" may be found from the following empirical expression .

$n = m + k \cdot (m)^{0.27}$

where "k" is 2.4 for $J_n(m) = 0.01$, and 3.5 for $J_n(m) = 0.001$.

For a single tone 15 kHz modulation with 75 kHz deviation, the modulation index is "5". If we ignore components with amplitudes less than 1% ($J_n(5)$C 0.01), the number "n" is 9. The bandwidth required is 270 kHz.

The signal bandwidth for stereo Left or Right only single tone 15 kHz modulation is typically less than that for monaural modulation. This is due to the reduction in modulation index. The frequency deviation is held constant at 75 kHz but the composite baseband spectral components comprise of modulation frequencies at 15 kHz ("L + R" Main Channel), 19 kHz (Pilot), 23 kHz and 53 kHz ("L - R" Subcarrier Channel). The bandwidth calculation for multiple tone or stereo FM modulation is quite complex because several combination frequencies must be accounted for. This is caused by the nonlinear process inherent to frequency modulation.

4.2.3 Effects Of Bandwidth Limitations

Typically, bandwidth limitations occur when the FM signal passes through the RF path comprising the transmitter, filterplexer/combiner, antenna system and the particularly in the receiver.

Figure 4 shows the effect of passing a twin-tone (10 kHz/25 kHz) modulated FM signal through a wideband and a narrowband (-3 dB bandwidth . of 400 kHz) RF path The top three pictures show that the wideband RF path has negligible effect on the demodulated audio signal. But the bottom three pictures show the distortion products caused by bandwidth restriction.

4.2.4 Effects On The Transmitter RF Intermodulation

Frequency Spectrum is a very limited natural resource. The FM broadcast band is shared by several users at the same location. When multiple signals are present, any non-linear device such as tube in the transmitter power amplifier will generate RF intermodulation products due to mixing of these multiple signals. This mixing will have some conversion loss called "turn-around-loss". The degree of intermodulation interference generated within a given system can be accurately predicted when the turn-around-loss of the transmitter is available.

Turn-Around-Loss depends on three factors

- In-band Conversion Loss
- Interfering Signal Attenuation due to PA Output Selectivity
- Attenuation of Resulting IM products due to PA Output Selectivity.

The transmitter with a narrower bandwidth will have higher selectivity thereby making it more immune to RF intermodulation. Therefore, there is certainly a trade-off between modulation performance and immunity from RF intermodulation.

4.3 RF POWER AMPLIFIER DESIGN CONSIDERATIONS

4.3.1 Primary Design Factors

The primary factors which should be considered in Power Amplifier design are:

- Desired Power Output
- Optimum Modulation Performance
- High Efficiency and Reliability
- Best Value for the Cost

This chapter will focus its discussion on the second item - the design considerations necessary to achieve the optimum modulation performance.

4.3.2 RF Power Ampliffer Bandwidth

The transmitter power amplifier bandwidth affects the modulation performance. Available bandwidth determines the amplitude response, phase response, and group delay response. There is a trade-off involved between the bandwidth, gain, and efficiency in the design of a power amplifier.

RF power amplifier bandwidth is restricted by the equivalent load resistance across parallel tuned circuits. Tuned circuits are necessary to cancel low reactive impedance presented by relatively high input and output capacitances of the amplifying device such as a vacuum tube.

The bandwidth for a single tuned circuit is proportional to the ratio of capacitive reactance X_c to load resistance, R_L (appearing across the tuned circuit

$$BW = \frac{K}{2\pi \cdot f_c \cdot C \cdot R_L} = \frac{K(X_c)}{R_L}$$

Where: BW = bandwidth between half-power (or -3 dB) points

K = proportionality constant

R_L = load resistance (appearing across tuned circuit)

C= total capacitance of tuned circuit (includes stray capacita ces and output or input capacitances of the tube

X_c = capacitive reactance of C

f_c = carrier frequency

The RF voltage swing across the tuned circuit also depends on the load resistance. For the same power and efficiency, the bandwidth can be increased if the capacitance is reduced.

4.4 Input Circuit Configurations And Their Effects On The Transmitter Amplitude and Group Delay Responses

Newer transmitter designs utilize solid-state intermediate power amplifiers to provide necessary RF drive level to operate the tube in the class C mode. The output load impedance is typically 50 Ohms. It is, therefore, necessary to design a matching network to transform a high grid input impedance to 50 Ohms at the PA input. The following three types of input matching circuit configurations are used:

Single Element Capacitive (C) Input Match

Single Element Inductive (L) Input Match

Broadband (L-C) Input Match.

The first two are the popular ones. These matching circuits have different effects on the PA amplitude and group delay responses.

4.4.1 Capacitive Input Match

Single Element Capacitive Input Matching Circuit is shown in Figure 4.1This is the simplest in design as well as implementation. Variable inductor "Lin" tunes out the tube input capacitance past parallel resonance to make the input impedance slightly inductive. This is necessary to transform the high grid impedance to an equivalent series 50 Ohms resistance and some inductive reactance. The reactance is then tuned out with a series variable capacitor, "Cs". Interactive adjustment of "Lin" and "Cs" is required. This configuration has the characteristics of a high pass filter.

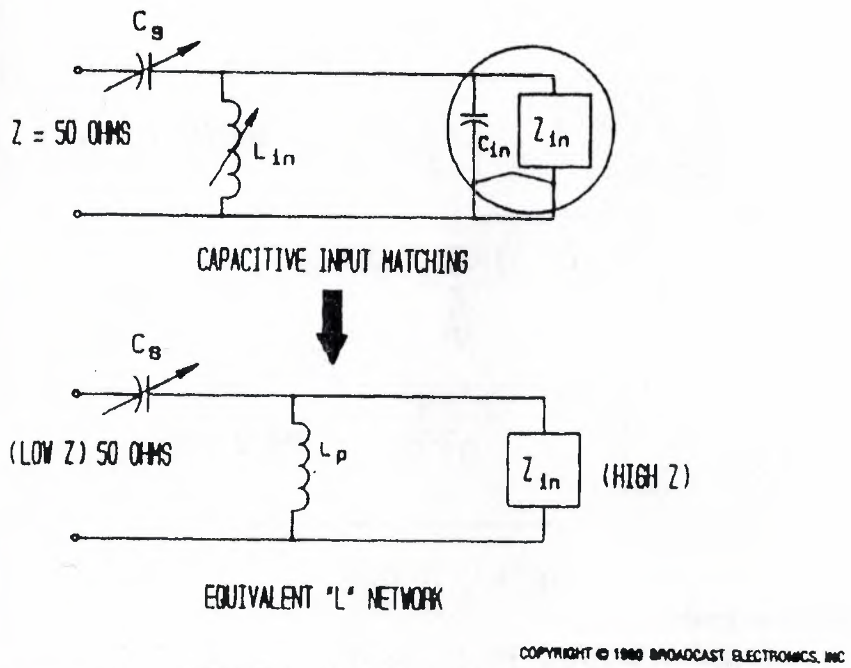


Figure 4.1 CAPACITIVE INPUT MATCHING CIRCUIT

4.4.2 Inductive Input Match

Single Element Inductive Input Matching Circuit is shown in Figure 4.2 This is the next most popular method for input matching. The variable inductor "Lin" is used to tune out the input capacitance slightly before the parallel resonance is reached, on the capacitive side. This is necessary to transform the high grid impedance to an equivalent series 50 Ohms resistance with some capacitive reactance. The reactance is then tuned out with a series variable inductor "Ls". Interactive adjustment of "Lin" and "Ls" is required. In this circuit configuration, a part of the input capacitance is used for impedance transformation and the equivalent capacitance across the tuned circuit becomes less, thereby increasing the bandwidth. This configuration has the characteristics of a low pass filter.

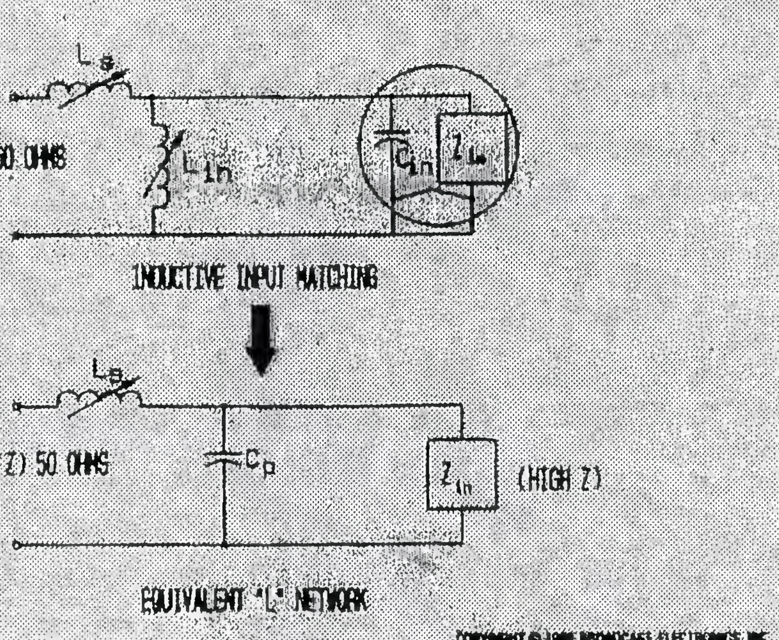


Figure 4.2 INDUCTIVE INPUT MATCHING CIRCUIT

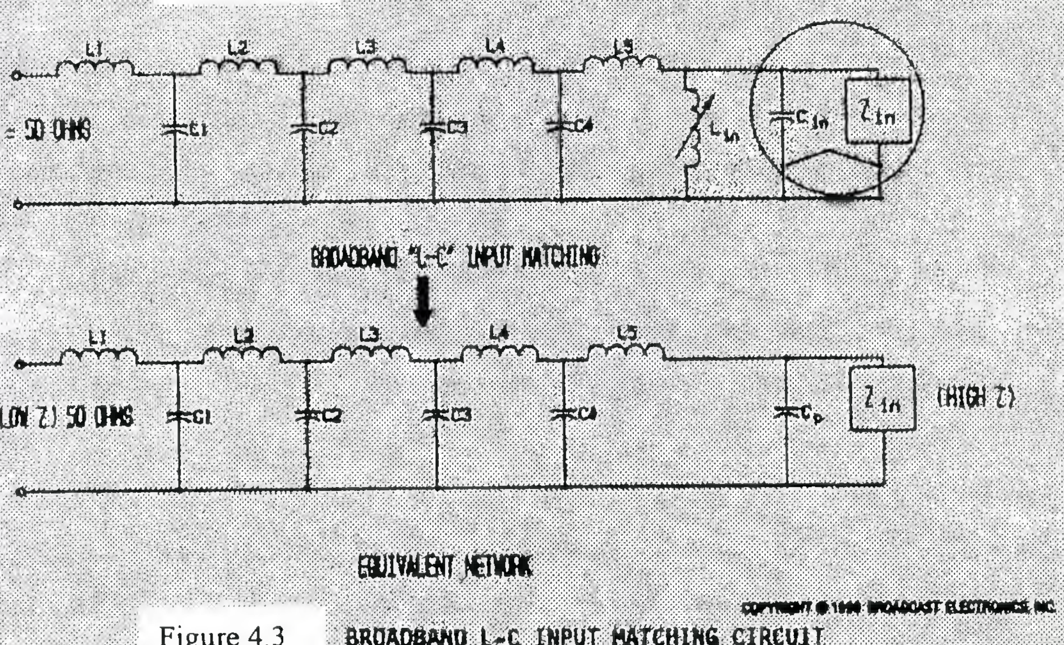


Figure 4.3 BROADBAND L-C INPUT MATCHING CIRCUIT

4.4.3 Broadband L-C Input Match

Broadband L-C Input Matching Circuit is shown in Figure 4.2. This is an extension of L-Match circuit. It utilizes multiple L-C sections with each section providing a small step in the total impedance transformation. This technique provides a broadband impedance match without interactive adjustment and improves the transmitter operation. This configuration also utilizes a part of the input capacitance for impedance transformation and has the characteristics of a multiple section low pass filter.

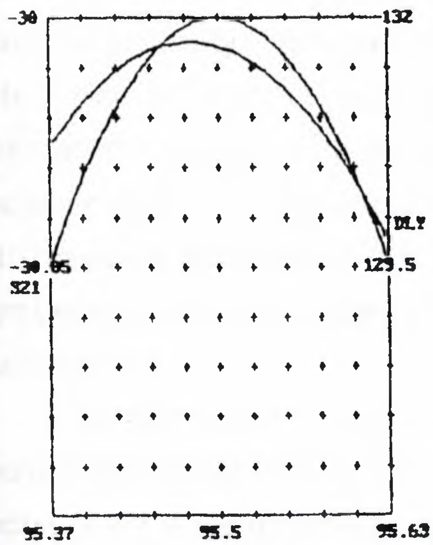
4.5 Computed And Measured Amplitude Group Delay Responses Of Capacitive And Broadband Input matching circuits

The results of computer analysis and actual measurements made with two different input circuit configurations, C-Match and Broadband L-C Match, in a real transmitter operating at 20 kW Rf power are presented below.

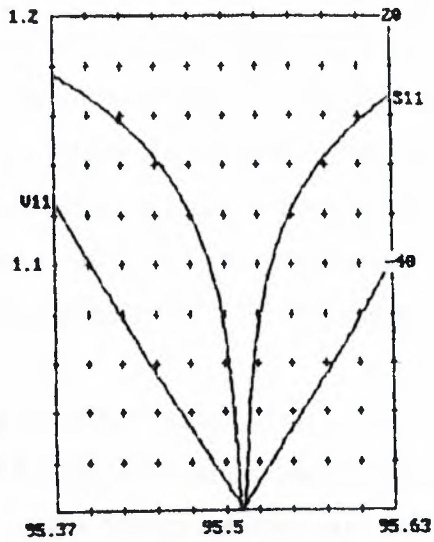
Two Input matching circuits were designed to transform the high impedance of PA input tuned circuit to 50 Ohms resistive impedance. For the purpose of illustration it was assumed that a total capacitance of 165 picofarads in parallel with 375 Ohms load resistance appeared across the tuned circuit. This represents the input impedance of a typical 20 kW FM transmitter power amplifier input circuit utilizing an Eimac 8989 tetrode.

Computer software programs ECA [11] and =SuperStar= [12] were used to analyze the circuit designs and obtain the response plots. Newlett Packard Network Analyzer Model 3577A was used to obtain the measured response plots.

Figure 14A shows the computed amplitude response (S21) and group delay (DLY) response plots for capacitive input matching circuit. Figure 14B shows the input VSWR (V11) and input return loss (S11) plots at - 0.05 dB response points. The peaks of amplitude and group delay plots do not coincide in the case of capacitive input matching circuit.



14A. AMPLITUDE (S21) AND GROUP DELAY (DLY)



14B. INPUT VSWR (V11) AND RETURN LOSS (S11) RESPONSES

FIGURE 14A – 14B . COMPUTEU AMPLITUDE, GROUP DELAY, VSWR, AND RETURN lOSS RESPONSES OF A CAPACITIVE INPUT MATCHING CIRCUIT.

In newer design transmitters, the tube power amplifier is typically constructed in a cavity enclosure utilizing (larger physical size coaxial transmission line section of either quarter-wavelength, or half-wavelength to increase the unloaded "Q" nnd minimize losses.

The Power Amplifier efficiency depends on the RF plate voltage swing developed across the load resistance, the plate current conduction angle and the cavity efficiency. The PA cavity efficiency is related to the ratio of loaded to unloaded "Q" as follows .

$$N = 1\ Ql \times 100 / QU$$

Where: N = efficiency in percent

Ql = loaded "Q" of cavity

QU = unloaded "Q" of cavity

The loaded "Q" is dependent on the equivalent plate load resistance presented across the tuned circuit and output circuit capacitance. Unloaded "Q" depends on the cavity volume and the RF resistivity of the conductors due to skin effects. A high unloaded "Q" is desirable, as is a low loaded "Q", for best efficiency. As the loaded "Q" goes up the bandwidth decreases. For a given tube output capacitance and power level, loaded "Q" decreases with decreasing plate voltage or with increasing plate current. The increase in bandwidth at reduced plate voltage occurs because the load resistance is directly related to the RF voltage swing on the tube element.

For the same power and efficiency, the bandwidth can also be increased if the output capacitance is reduced. Power tube selection and minimization of stray capacitance are areas of particular concern in PA design for maximum bandwidth. Bandwidth can be further improved by minimizing added tuning capacitance and by properly selecting the output coupling method.

The following are the two popular methods of output coupling circuits used:

- Series Capacitive Output Coupling
- Magnetic Output Coupling Loop.

These circuits have different effects on the PA amplitude and group delay responses.

4.5.1 Series Capacitive Output Coupling

Figure 20 shows a schematic of a tetrode power amplifier with a capacitive output tuning and capacitive output coupling circuit .

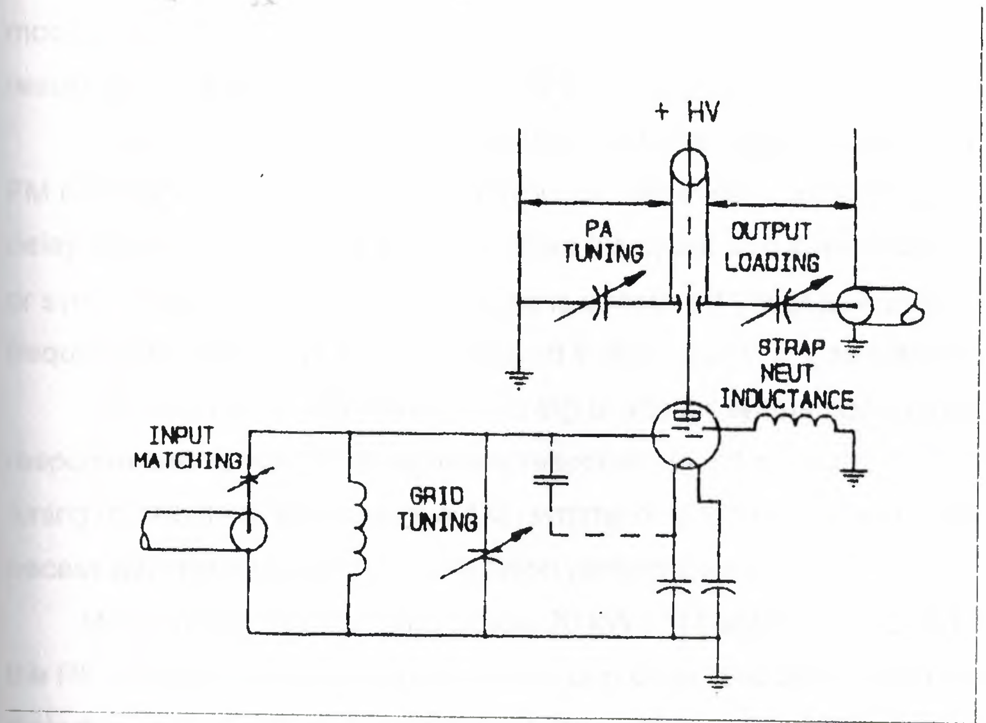


FIGURE 20. TETRODE POWER AMPLIFIER CIRCUIT WITH CAPACITIVE OUTPUT TUNING ANO CAPACITIVE OUTPUT COUPLING

Acapacitive output coupling circuit was designed to transform the high impedance of the PA output tuned circuit (with total capacitance of 20 picofarads and 1590 Ohms load resistance across it) to 50 Ohms. This illustrates the output circuit of a typical 20 kW FM transmitter PA utilizing an Eimac 8989 tetrode. Computer software programs ECA and
=SuperStar= were used to analyze the circuit design and obtain the response plots.

4.6 EFFECTS OF RF POWER AMPLIFIER TUNING ON FM MODULATION PERFORMANCE

In an FM broadcast transmitter, the RF power amplifier is typically adjusted for minimum synchronous AM (incidental amplitude modulation) which results in symnetrical amplitude response. This will assure that the transmitter's amplitude passband is properly centered on the FM channel. The upper and lower sidebands will be attenuated equally or symnetrically which is assumed to result in reduced modulation distortion. This will be true if the power amplifier circuit topology results in simultaneous symnetry of amplitude and group delay responses.

Actually, synmetry of the group delay response has a much greater effect on FM modulation distortion than the amplitude response. Tuning for symetrical group delay will cause the phase errors to affect the upper and lower sidebands equally or symnetrically. Group delay response is constant if the phase shift versus frequency is linear. The signal is delayed in time, but no phase distortion occurs.

In most FM transmitters, the tuning points for symnetrical amplitude response and symetrical group delay response do not coincide. Therefore, simply tuning for minimum synchronous AM (symmetrical amplitude response) does not necessarily result in best FM modulation performance.

Measurements taken on a typical 20 kW FM transmitter showed that tuning the RF power amplifier for symmetrical group delay response resulted in minimum distortion and crosstalk. It confirms that group delay response asymnetry causes higher FM modulation distortion and crosstalk than the amplitude response asymmetry. Therefore, RF power amplifier circuit topologies that exhibit coincidence of symmetrical amplitude and group delay responses will result in a better overall FM modulation performance.

5. IMPROVING FM MODULATION PERFORMANCE BY TUNING FOR SYMMETRICAL GROUP DELAY

5.1 INTRODUCTION

FM Broadcast Engineers need a simple and effective procedure to tune FM transmitter power amplifier(s) for best FM modulation performance. Over the past several years, procedures for tuning the amplifier(s) for minimum synchronous AM (ICAM) resulting from FM modulation have beed used with some success to improve FM modulation performance. This paper explains an alternative tuning procedure that offers further improvements in FM modulation performance. The new procedure involves tuning the amplifier(s) for symmetrical group delay instead of minimum synchronous AM (ICAM). Before getting into this procedure,the terminology needs to be defined.

5.2 Synchronous AM

The perfect FM transmitter would have anabsolutely constant output amplitude, regardless of FM modulation or power supply variations. A practical FM transmitter produces an output which varies in amplitude as well as frequency. The portion of the amplitude variation resulting from the FM modulation is called Synchronous AM. Synchronous AM, also referred to as Synchronous AM Noise of Incidental Carrier AM (ICAM), is a measure of the amount of incidental amplitude modulation introduced onto the carrier by the presence of FM modulation. Since all transmitters have limited bandwidth, there will be a slight change in power output as the carrier frequency is swept to either side of the center frequency. This change in RF output level follows the waveform of the audio frequency being applied to the FM modulator causing AM modulation in synchronization with the FM modulation. This concept is similar to the slope detection of FM by an AM detector used in conjunction with a tuned circuit. The technical paper entitled Optimum Band-width for FM Transmission.[1] provides further insight into the overall bandwidth required to achieve a given level of FM modulation performance.

Synchronous AM measurements give the station engineer a rough idea of the overall system bandwidth and whether the transmitter is tuned to position the amplitude pass-band correctly.

5.3 Symmetrical Group Delay

Another way in which practical transmitters deviate from the ideal, is the group delay response. Group delay refers to the propagation time delay variations between a group of several different frequency components (FM sidebands) propagating through the transmitter power amplifier(s). Each different frequency component (FM side-band) will pass through the input and output network(s) at a slightly different rate, so that the FM sidebands in the group are not all delayed equally in time, hence the term Group Delay refers to the total time delay variation of the group of FM sidebands.

Symmetrical Group refers to a tuning condition that causes the Group Delay (time) variations to be equal above and below the center frequency of the transmitter.

Another way of viewing Group Delay, is to observe the phase shift of each FM side-band passing through the output amplifier(s). If each FM sideband is phase shifted linearly with frequency, the Group Delay (time) will be constant. Constant Group Delay is therefore equivalent to linear phase shift with frequency. A properly terminated piece of transmission line provides constant group delay and linear phase shift. All components of the signal are delayed equally in time and no phase distortion occurs.

5.4 FM Modulation Performance

For the purpose of this presentation, FM modulation performance is defined as the overall quality of the FM base band information transmitted to the consumer. Quality factors inclued the amount of harmonic distortion, intermodulation distortion, stereo separation, and crosstalk between subcarriers. Factors which are not part of the demodulated baseband include AM signal to noise ratios that do not directly affect FM modulation performance.

5.4.1 LIMITATIONS OF SYNCHRONOUS AM MEASUREMENTS

Synchronous AM measurements are an indirect way of evaluating and optimizing FM performance. Even though synchronous AM measurements are a helpful aid to begin tuning an FM transmitter, these measurements tell only the amplitude response half of the total story. Transmitter tuning also affects the group delay (time) response which changes the relative time delays of the higher order FM sidebands. FM broadcast transmitter RF power amplifiers are typically adjusted for minimum synchronous AM. This results in a symmetrical amplitude response by centering the transmitter.s amplitude passband on the FM channel. The upper and lower sidebands will be attenuated equally or symmetrically which is assumed to result in optimum FM modulation performance. This would be true if the RF power amplifier circuit topology resulted in simultaneous or coincidental symmetry of the amplitude and group delay responses.

The tuning points for symmetrical amplitude response and symmetrical group delay response normally do not coincide, depending on the circuit topology of the RF power amplifier. Therefore, simply tuning for minimum synchronous AM (symmetrical amplitude response) normally does not result in best FM modulation performance. The technical paper entitled .The Significance of Power Amplifier Circuit Topology on FM Modulation Performance.[2] provides detailed information about various power amplifier circuit topologies.

5.4.2 Symmetrical Amplitude (Synchronous AM) versus Symmetrical Group Delay Response

A computer simulation called FMSIM[3] was jointly developed and Quantics Software to explore the effects of the transmitter output network(s) and FM filterplexing systems on FM modulation performance. FMSIM allows the effects of the Amplitude Response to be independently compared with the effects of Group Delay response. The independent evaluation of amplitude versus group delay effects are difficult or impossible to do empirically since the amplitude and group delay responses are inseparable in a real network. The results of these simultaneous showed that amplitude differences between the upper and lower sidebands of the FM signal have little direct effect on FM modulation performance, while Group Delay (time) differences between the upper and lower sidebands have a much more profound effect on FM modulation performance. Furthermore, the analysis revealed that when the group delay is symmetrical above and below the carrier frequency, the total FM distortion is minimized. In particular, the even order (2nd, 4th, 6th,...) harmonics of the audio modulating frequency drop out. Figure-2 shows a similar spectogram from the same power amplifier that has been retuned for a symmetrical group delay response centered on the carrier frequency. Note that only odd order distortion products are now visible. This effect leads to a simple, low cost procedure for tuning the amplifier(s) to this condition without the use of network analyzers or other complicated test equipment.

Figure5.1 shows a spectogram of baseband distortion products from a power amplifier that is tuned for a symmetrical amplitude response (minimum synchronous AM) with an asymmetrical group delay response. Note that both even and odd order distortion products are visible in the demodulated baseband. Condition without the use of network analyzers or other complicated test equipment. Tuning for Best FM Modulation Performance Tuning for minimum synchronous AM is a good starting point, but it is desirable to finish tuning at the symmetrical group delay point. Fine tuning the input and output for minimum even order harmonic distortion will optimize the group delay (time) response. Tuning the transmitter for minimum even order harmonic distortion will result in a symmetrical group delay response and optimum FM modulation performance. This can be accomplished by: (1) observing the even order hamonics in the demodulated baseband with a spectrum analyzer or by (2) placing an audio bandpass filter (tuned to the second harmonic of the audio modulating frequency) on the input of the audio distortion anaylyzer.

Most FM stations have an FM stereo modulation monitor with a 19kHz bandpass filter and metering circuitry that is normally used to measure the 19kHz pilot tone injection level. This monitor function can also be used to tune for symmetrical group delay if the transmitter is 100% modulated with a single 9.5kHz monaural tone without 19kHz pilot. The second harmonic distortion produced by transmitter amplifier(s) mistuning will fall within the 19kHz bandpass of the monitor.s pilot injection level metering andwill appear as if there was a pilot tone present. Tuning the transmitter power amplifier(s) for a minimum pilot injection level indication will null the second and other even order harmonics of the 9.5kHz modulating tone resulting in symmetrical group delay of the sidebands.If the FM station does not have a suitable stereo odulation monitor, a simple 19kHz bandpass filter can be inserted between the composite output of the RF to baseband demodulator and the audio voltmeter. The transmitter is then tuned for minimum audio voltage produced by second harmonic distortion.

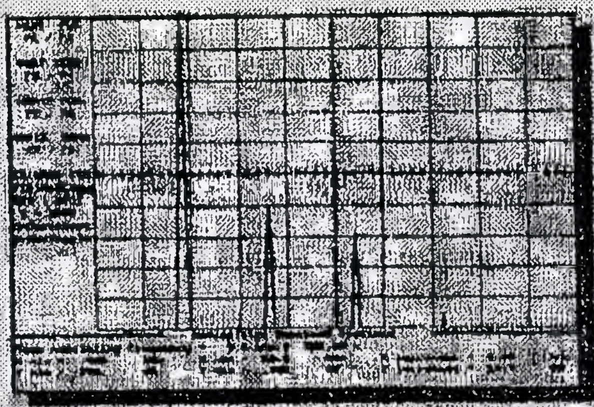


FIGURE 5.1

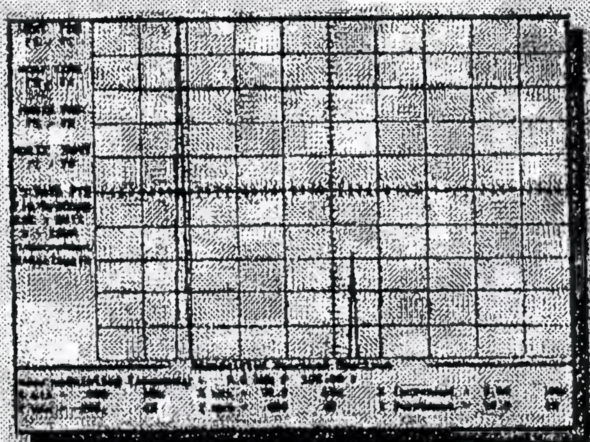


FIGURE 5.2

The passive 19kHz bandpass filter can be purchased from one of the companies shown in the references[4] or it can be easily constructed out of readily available inductors and capacitors[5] according to the schematic shown in Figure-5.3.Figure-5.4 shows the amplitude response and insertion loss of the 19kHz bandpass filter illustrated Figure-5.3.

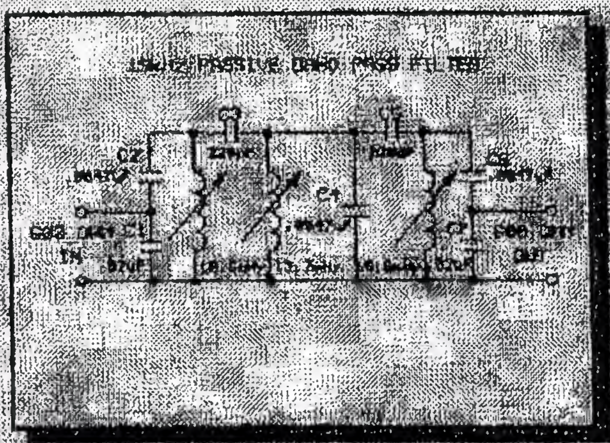


FIGURE 5.3

Figure-4 shows the amplitude response and insertion loss of the 19kHz bandpass filter illustrated Figure-3.

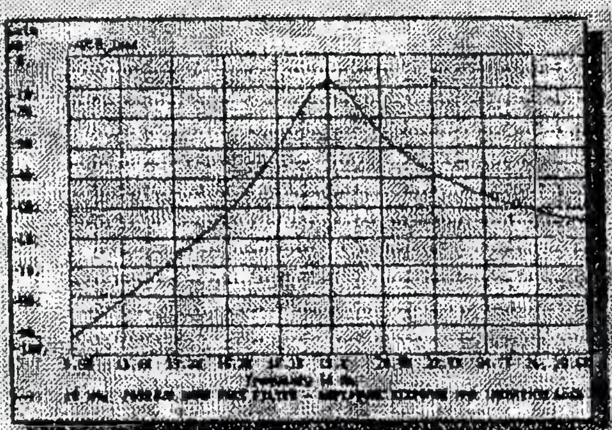


FIGURE- 5.4

The 19kHz filter should have at least 80 dB rejection of the 9.5kHz modulating tone and at least 50 dB rejection of the third and higher harmonics of 9.5kHz. Be certain that the FM demodulator has good linearity and does not introduce distortion products that would cause the broadcast engineer to mistune the transmitter to compensate for the distortion introduced by the demodulator.

Modulation monitors that utilize a pulse-counting discriminator are usually the most dependable for this measurement.

6. TECHNIQUES FOR MEASURING SYNCHRONOUS AM NOISE IN FM TRANSMITTERS

6.1 INTRODUCTION

This paper presents an explanation of synchronous AM noise caused by FM modulation of limited bandwidth systems. Synchronous AM noise is presently one of the "hottest" topics among FM and TV-Stereo broadcast engineers. The causes of this type of incidental AM modulation in the presence of FM modulation are reviewed with emphasis on the practical application of synchronous AM noise measurements to optimize transmitter tuning.

The value of synchronous AM measurements in evaluation the transmission system as well as test equipment selection, system set-up, and interpretation of results are explained. The type of equipment and measurement procedure used can lead to incorrect results. The author explains how to avoid these "pitfalls" so that the station engineer has confidence that the measured results are correct. It is hoped that this paper will be a valuable reference that broadcast engineers can use to improve the operation of their transmitter systems.

6.2 TWO TYPES OF AM MODULATION

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

1. Asynchronous AM modulation is measured without FM modulation and is primarily related to power supply ripple or filament supply imbalance. This is the only type of AM noise measurement that is required by the FCC.

2. Synchronous AM modulation (incidental AM) measured with FM modulation is elated to the tuning and overall bandwidth of the system. Synchronous AM noise s not a concern of the FCC.

6.2.1 Asynchronous AM

Residual amplitude modualtion of the transmitter output, due primarily to power supply ripple, is measured with an AM envelope detector. Most FM modulation onitors include an AM detector for this purpose. This detector should include 5 microsecond de-emphasis on its output. The residual AM noise in a properly perating FM transmitter will be at least 50 dB below the level which would represent 00 percent amplitude modulation of the carrier. If the transmitter is unable to eet the 50 dB requirement, the problem can usually be traced to a power supply omponent including the filament supply or to line imbalance in a three phase system.

6.2.2 Synchronous AM

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

Both types of AM noise measurements are made directly at the transmitter output (or an accurate sample of its output). No amplifying or limiting equipment may be used between the transmitter output and the AM detector since nonlinearities this equipment could modify the AM noise level present. Since the transmitter cannot be fully amplitude modulated, an equivalent reference level must be established indirectly by a measurement of the RF carrier voltage.
Refer to the instructions of the detector manufacturer to determine this reference level. Generally, the reference level is determined by setting a carrier level meter to a specified reading or to obtain a specific DC voltage level at the output of the detector diode without modulation.

6.3 WHY IS SYNCHRONOUS AM IMPORTANT?

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

6.3.1 How Does Tuning Affect The FM Sidebands?

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

6.3.2 How Good Should Synchronous AM Be?

Synchronous AM of 40 dB or more below equivalent 100% AM, is considered to be acceptable. Higher levels of synchronous AM will cause increased "chopping" of the signal at the receiver near limiting threshold under weak signal "fringe area" conditions and can exacerbate multipath problems. Excessive synchronous AM is also an indirect indication of passband induced distortion problems that degrade stereo performance and SCA crosstalk.

Many of the older mult-tube transmitter designs presently in use will have as much as 6% (-30 dB) synchronous AM when simply tuned for best power output and efficiently even though the asynchronous AM (without modulation) may be better than -50 dB. Some of the newer single tube transmitters can be adjusted for 50 dB or more suppression of synchronous AM. The synchronous AM level of virtually any FM transmitter can be improved by proper tuning techniques. An approximation to the overall system bandwidth can be related to the synchronous AM as shown in Table 1.

APPROXIMATE SYSTEM BANDWIDTH AS RELATED TO SYNCHRONOUS AM

SYNCHRONOUS AM (below equivalent 100 % AM LIMITER (with +75 kHz @ 400 Hz FM)	APPROXIMATE BANDWIDTH OF TRANSMITTER (-3dB)	RF LEVEL VARIATION AT RECEIVER (%)	(dB)
-30 dB	410 kHz	6.32%	0.57 dB
-35 dB	550 kHz	3.54%	0.31 dB
-40 dB	730 kHz	2.00%	0.18 dB
-45 dB	1.00 MHz	1.12%	0.10 dB
-50 dB	1.34 MHz	0.64%	0.06 dB
-55 dB	1.82 MHz	0.36%	0.03 dB
-60 dB	2.46 MHz	0.20%	0.02 dB

TABLE 1.

TUNING YOUR TRANSMITTER FOR PEAK PERFORMANCE

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

6.4 Inital Tuning And Loading

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

6.4.1 Input Tuning And Matching

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

6.5 Output Tuning

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

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

6.5.1 Output Loading

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

6.6 Automatic Power Control Headroom

Automatic power control (APC) feedback systems are utilized in many transmitters to regulate the power output around a predetermined setpoint with variations.

AC line voltage or changes in other operating paramenters. Most modern FM broadcast transmitters utilize a high gain tetrode as the final amplifier stage with adjustment of the screen voltage providing fine adjustment of the output power.

For each power output level there is one unique combination of screen voltage and output loading that will provide peak operating efficiency. If the screen voltage is raised above this point without a corresponding increase in loading, there will be no further increase in power output with rising screen voltage and screen current. If the screen voltage is raised without sufficient loading, a screen current overload will occur before the upward adjustment in power output is obtained.

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

6.7 MINIMIZING SYNCHRONOUS AM

After the correct loading point has been set, FM modulate 100% (+75 kHz) at 400 Hz and fine-adjust the transmitter's input tuning and output tuning controls for minimum 400 Hz AM modulation as detected by a wideband envelope detector (diode and line probe). The input matching and output loading controls should need no further adjustment at this point. It is helpful to display the demodulated output from the AM detector on an oscilloscope while making this adjustment. The output of the AM envelope detector should be connected to the vertical input (Y input) of the scope while the sweep is triggered by a sample of the 400 Hz audio tone fed to the external trigger input. This is called the "AM WAVEFORM" measurement. Note that as the minimum point of synchronous AM is reached, the demodulated output from the AM detector will double in frequency form 400 Hz to 800 Hz, because the fall-off in output is symmetrical about the center frequency causing the amplitude variations to go through two complete cycles for every one FM sweep cycle. This effect is illustrated in Figure-6.1.

The advantages of observing the demodulated AM waveform versus time, is the frequency doubling effect is a sensative, clear, indication of symmetrical tuning point and the actual level of the AM noise below equivalent 100% AM modulation can be calculated from the waveform's AC and DC components. The disadvantage of this measurement technique, is that it cannot be performed with normal program audio present.

If it is necessary to touch-up the transmitter tuning with normal program audio present, an X - Y display of demodulated AM on the vertical axis (Y input) versus the audio input to the FM exciter on the horizontal (X input) axis, will provide a representation of the transmitter's passband as shown in Figures –6. 2A and6. 2B. This is called the "PASSBAND" measurement. Figure – 6.2A shows the relative amplitude of the transmitter's output power versus deviation from the center frequency with single tone 400 Hz modulation. Figure –6. 2B shows the same information except that complex program modulation is present.

When making the "PASSBAND" measurement on stereo multiplex transmissions, best results will be obtained if the horizontal input of the scope is driven by a sample of the composite baseband being fed to the FM modulator rather than L+R program audio. A sample of the composite baseband being fed to the FM modulator can be conveniently obtained from the front panel composite test jack provided on some FM exciters.

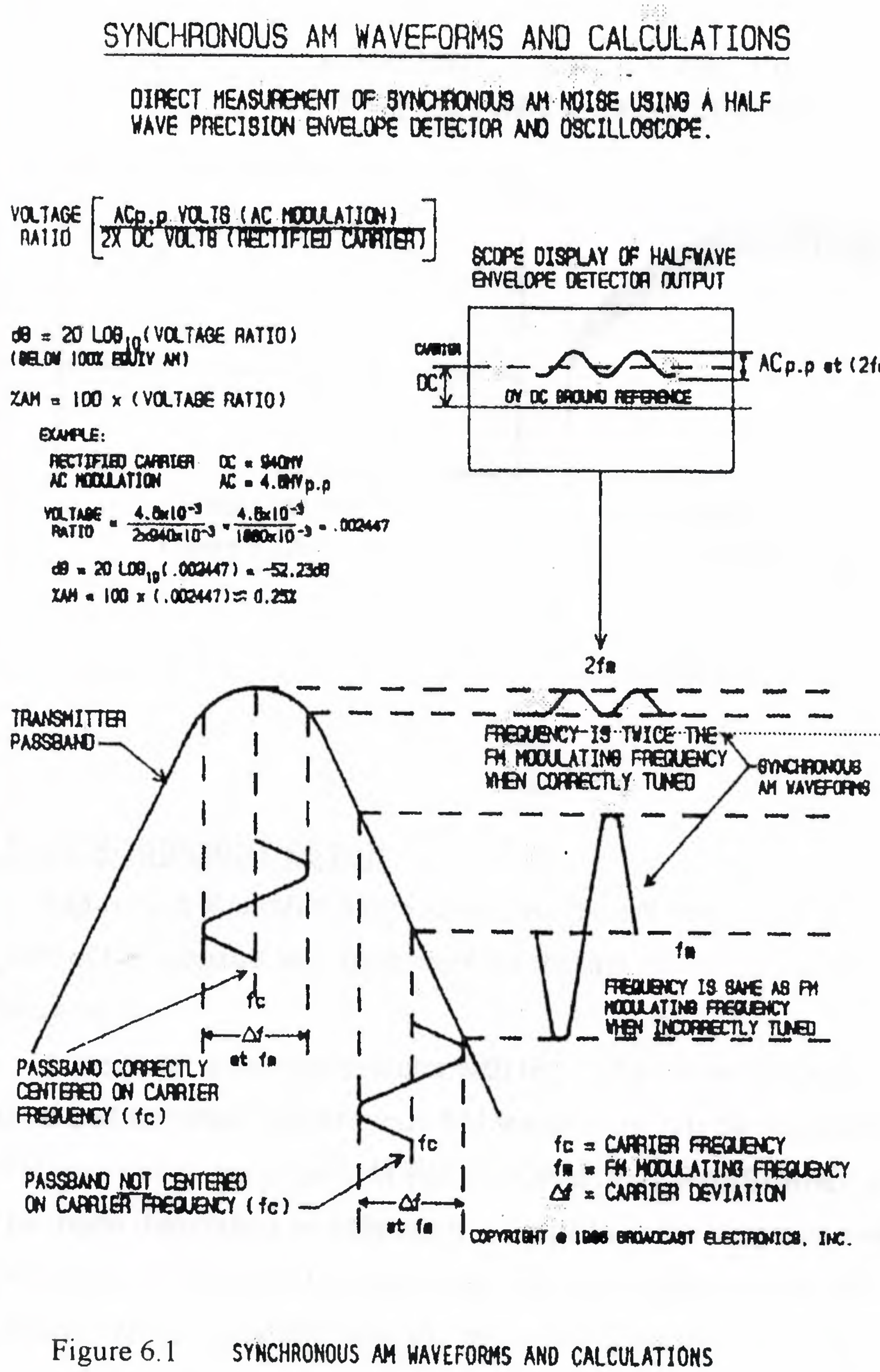
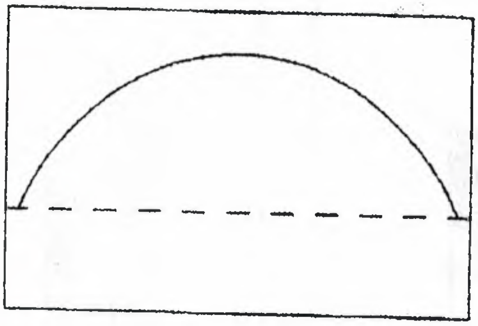


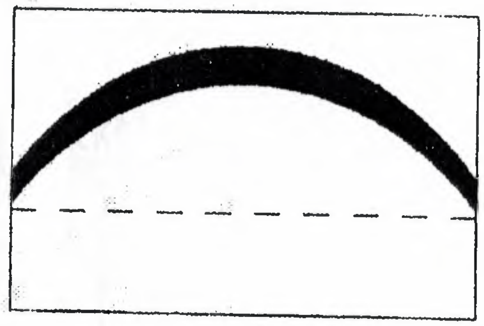
Figure 6.1 SYNCHRONOUS AM WAVEFORMS AND CALCULATIONS

X(HORIZONTAL) VERSUS Y(VERTICAL)
"PASSBAND" WAVE FORMS SHOWING SYNCHRONOUS AM



400Hz TEST TONE

Figure 6.2A



WITH TYPICAL PROGRAM MODULATION

Figure 6.2B

6.8 TEST EQUIPMENT SETUP

Figure-6. 3 illustrates a typical test equipment setup and shows a block diagram of the required test equipment for making synchronous AM waveform measurements.

A precision envelope detector with high return loss (low input VSWR) is used so that accurate synchronous AM waveforms can be observed while tuning the FM transmitter. Both the "AM WAVEFORM" and "PASSBAND" measurements can be made depending on whether the scope is in the triggered sweep mode or the X-Y mode. Composite baseband can also be routed into the test setup so that fine tuning can be done with normal programming being broadcast. It should be possible to minimize synchronous AN while maintaining output power and sacrificing little efficiency in a properly designed power amplifier. De-emphasis should NOT be used after the precision envelope detector, since the additional phase shift to the demodulated AM (Y-axis) caused by de-emphasis would not be equal to the phase shift of the composite baseband fed to the X-axis of the display.

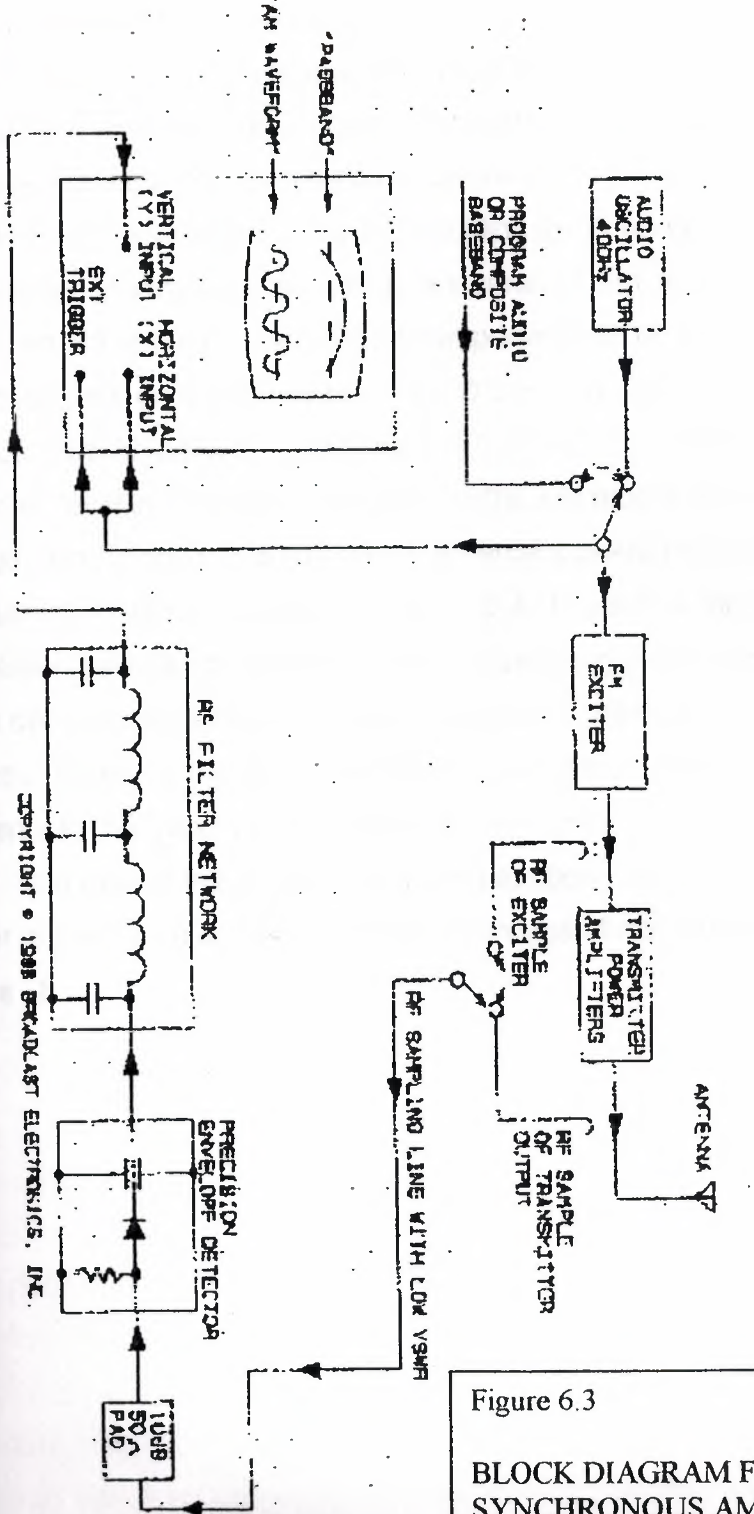


Figure 6.3

BLOCK DIAGRAM FOR SYNCHRONOUS AM MEASUREMENTS

6.9 CALCULATING AM NOISE DIRECTLY FROM THE DEMODULATED AM WAVEFORM

Most FM demodulators cannot be relied upon to make accurate asynchronous AM noise measurements so it is a good idea to cross check the demodulator reading directly against the demodulated output of a precision envelope detector. This can be done by first measuring the DC component of the waveform with a voltmeter or by DC coupling the scope input. The scope is then AC coupled and the input sensitivity is increased until an accurate peak to peak measurement of the AC modulation component can be made. The peak to peak AC voltage is then divided by twice the DC component to obtain the "VOLTAGE RATIO". Twenty times the LOG (base 10) of the "VOLTAGE RATIO" is the actual AM noise level in dB below equivalent 100% AM modulation. Multiplying the voltage ratio by one hundred yields the percent of AM modulation. Figures 6.1 and 6.4 illustrate these calculations. Figure – 6.4 shows how the percentage of AM modulation can be calculated by directly observing the RF envelope or by the use of the de-modulated waveform from a precision half-wave (peak) envelope detector. Note that the "peak" detected value of the carrier must be doubled to convert it to the "peak-to-peak" value of the carrier.

The ratio of the "peak-to-peak" modulation component to the "peak-to-peak" carrier is then used to calculate the percentage of AM modulation as illustrated in Figure –6. 4.

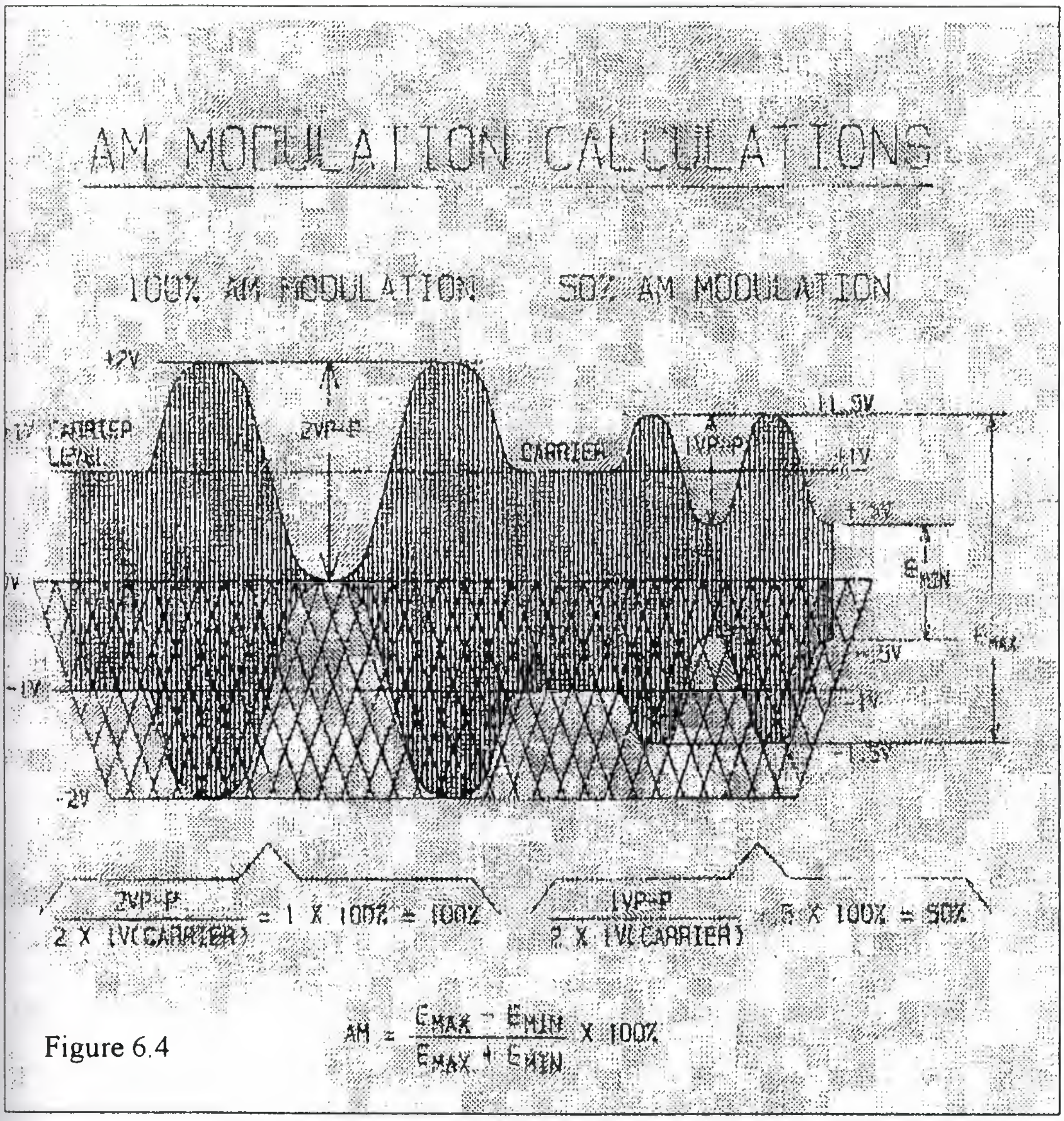


Figure 6.4

6.9.1 The Need For A Percision Envelope Detector

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

The input impedance of the envelope detector must provide a nearly perfect match so that there is a very low VSWR on the sampling line. Any significant VSWR on the sampling line will produce synchronous AM at the detector because the position of the voltage peak caused by standing wave moves along this line with FM modulation

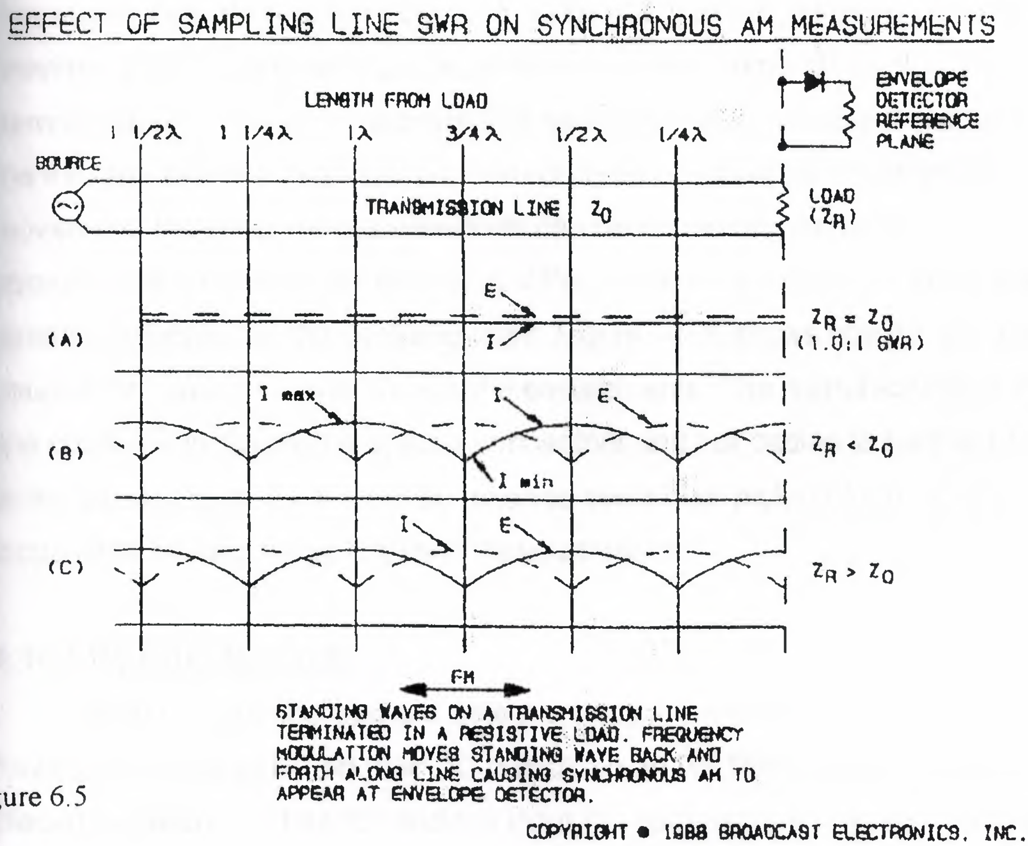


Figure 6.5

IGURE 5. EFFECT OF SAMPLING LINE SWR ON SYNCHRONOUS AM MEASUREMENTS

Figure – 6.5 illustrates the effect of the standing wave ratio on the RF voltage presented to the envelope detector. As the sampling line length is increased, the amount of erroneous AM caused by a given standing wave ratio also increases because each additional quarter wavelength causes more movement of the standing wave with FM modulation. Unfortunately, the AM detectors supplied with most modulation monitors do not provide a good enough match to be useful for this measurement.

Precision envelope detectors are available from Wide Band Engineering Inc. (model A33) and Hewlett Packard (mode 8471A option 004) that provide a 30 dB return loss (1.06:1 VSWR) to the sampling line when combined with a 10 dB, 50 ohm resistive pad.

6.10 Thru-Line Alternative To Percision Envelope Detector

A thru-line type directional coupler normally used to drive the wattmeter movement, has the envelope detector diode built into the sampling element and provides a DC component that the meter movement responds to plus the demodulated AM noise component that meter movement does not respond to. If the thru-line element output is fed to an oscilloscope instead of the wattmeter movement, the synchronous waveform can be accurately measured. This approach eliminates the errors due to VSWR on the sampling line, since the detector is located at the sampling point. Figure – 6.6 shows how to use a thru-line coupler for making synchronous AM measurements. The manufacturer of the thru-line coupler can supply the special connectors and / or cables to connect its output to the oscilloscope. Care must be taken to avoid hum pick-up from AC ground loops while making these low level measurements.

6.10.1 RF Filter Network

Both the thru-line element detector and the precision envelope detectors have some residual RF on their DC output, so an RF filter network should be placed between the detector and the input the oscilloscope. Figure - 6 shows a suggested configuration for this filter which can be easily constructed in a small shielded enclosure.

Built-In AM Noise Measurement Capability. A calibrated front panel AM noise test jack will allow observation of the synchronous AM waveform or direct measurement of the synchronous AM noise level on a standard audio voltmeter.

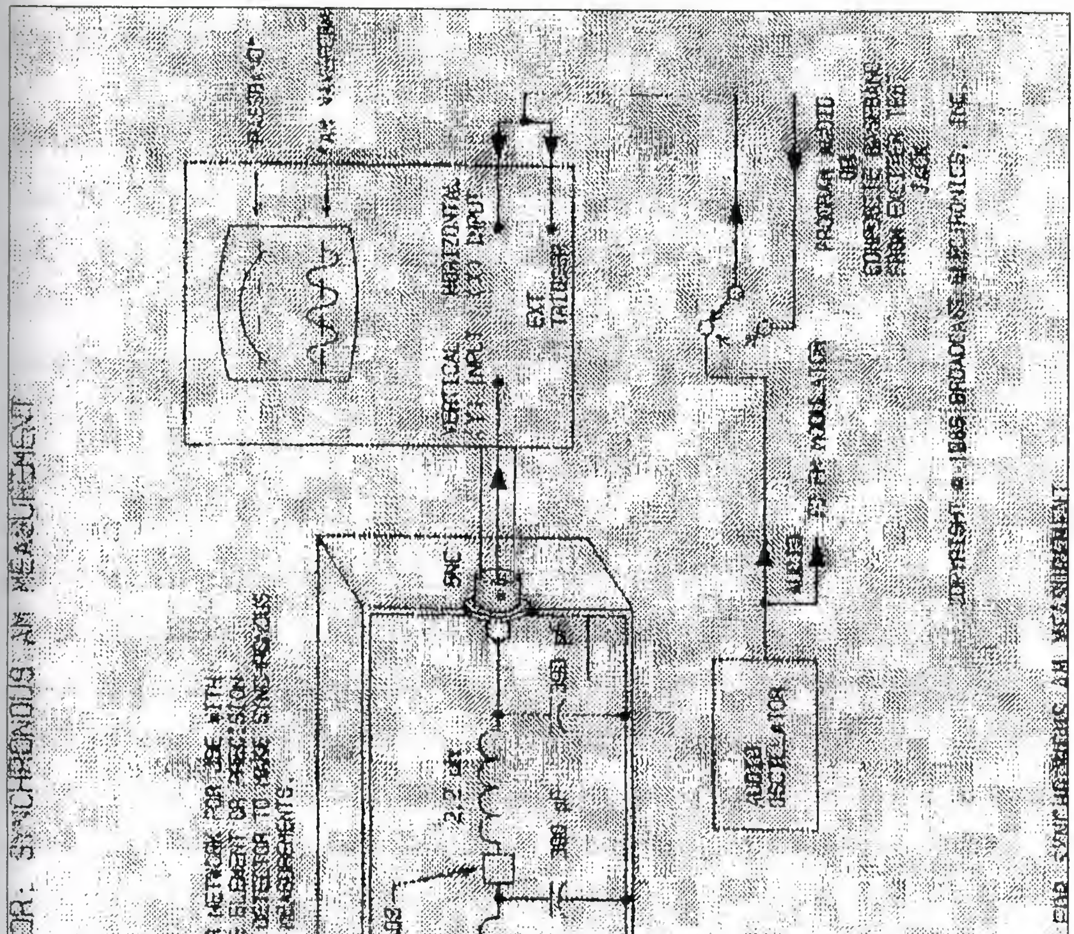

DETECTOR SETUP FOR: SYNCHRONOUS AM MEASUREMENT
FERRITE BEADS
BNC
AUDIO OSCILLATOR
EXT. TRIGGER
D.C. + AM MODULATION

Figure 6.6

6.11 MINIMUM SYNCHRONOUS AM VERSUS EFFICIENCY

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

Figures 6.7A thru 6.7D show the effect of output loading and efficiency on the shape of the passband. In Figures 7A and 7B, the "WAVEFORM" and "PASSBAND" are asymmetrical even though the minimum synchronous AM point has been reached. The +75 kHz points have an equal reduction in power output causing minimum synchronous AM, but the shape of the passband between those points is asymmetrical with peak power output occurring below the center (inductive side) of the passband (carrier frequency). Light loading at or beyond peak efficiency operating point causes increasing amounts of this asymmetry and results in increasing amounts of distortion to the FM signal passing through the amplifier. This effect is believed to be caused by the non-linear gain characteristics of the power amplifier tube operating on an elliptic load line.

Figures 7C and 7D show nearly perfect symmetry in both the "WAVEFORM" and "PASSBAND" with further reduced amounts of synchronous AM. This is due to heavier loading than required to get peak efficiency. Operating with heavier loading will; reduce the total amount of synchronous AM, improve symmetry of the passband, increase the width of the passband, and ultimately reduce the amount of distrotion to the FM signal. The amount of synchronous AM can be minimized at any particualr loading point by tuning the plate, but each change in loading has a new tuning point for minimum synchronous AM. What is the optium point? How much effeciency can be sacrificed?

While increasing amounts of loading will result in the above mentioned benefits, it carries with it the penalty of reduced PA efficiency, so there is a compromise between acceptable synchronous AM and efficiency. A properly designed and neutralized transmitter should be able to achieve acceptable synchronous AM without giving up more than about 3% in PA efficiency.

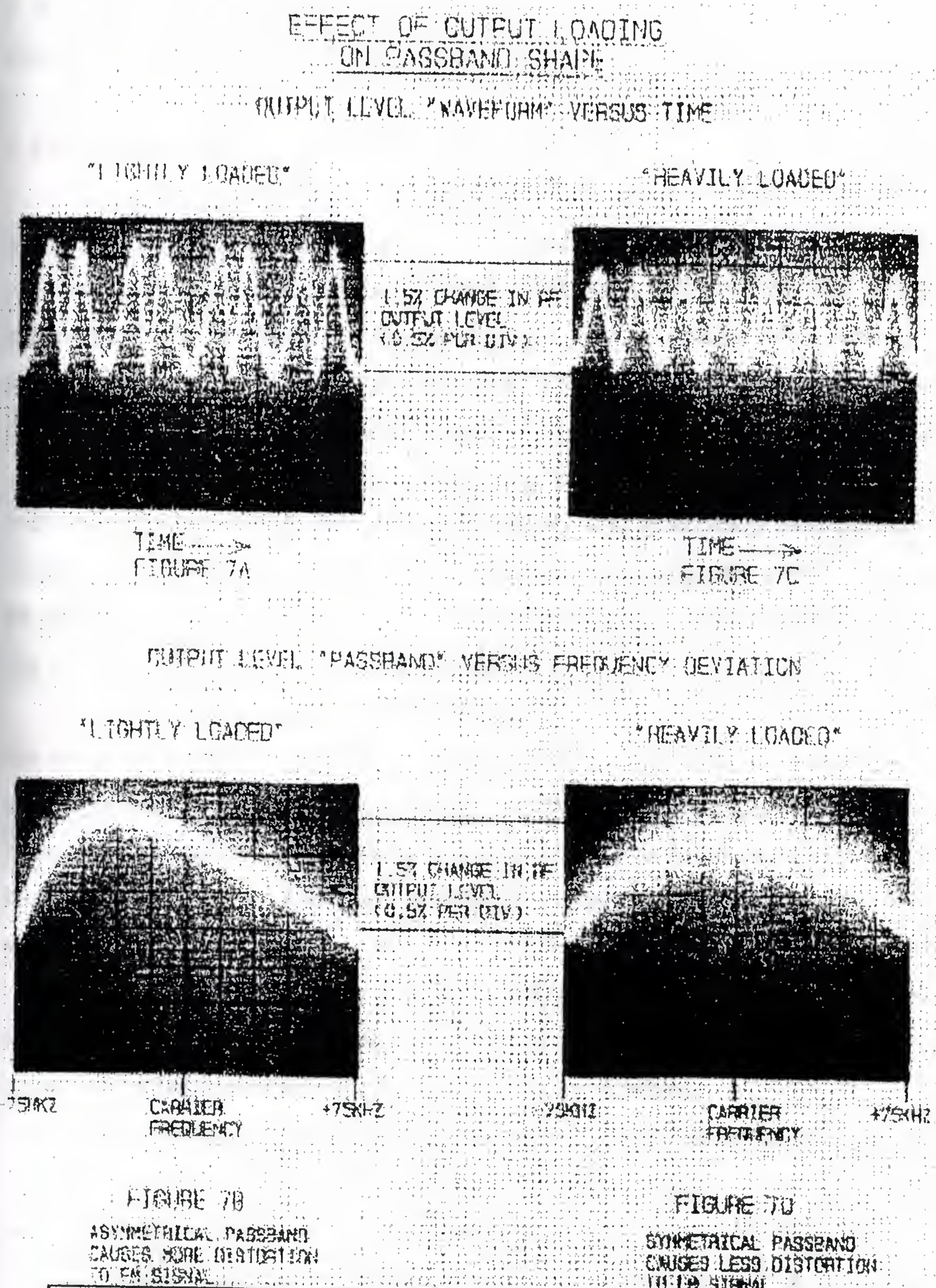


FIG.7 EFFECT OF OUTPUT LOADING ON PASSBAND SHAPE

7. PRACTICAL CONSIDERATIONS FOR THE IMPLEMENTATION OF A RELIABLE SYNCHRONOUS FM BOUSTER

7.1 INTRODUCTION

On July 16, 1987, the FCC adopted Docket MM 87-13 which authorized FM stations to increase the power of their on frequency booster facilities from 10 watts maximum to "20 percent of the maximum permissible ERP for the class of primary station they rebroadcast". The station may not, however, transmit beyond the predicted 1 mv/ n contour of the main transmitter for Class A and Class C stations, the 0.5 nv/m contour for Class B, or the 0.7 mv/m contour for Class B1 stations.

This decision has created a surge of interest from broadcasters as to the feasibility of a booster for their particular station, and specifically what means are available to accomplish this. The increase in power brings with it new problems to be dealt with, including widened interference zones, adequate signal ratios, and the need to synchronize carrier frequencies.

This chapter will deal with basic properties of "real world" effects caused by the presence of two or more radio signals of identical frequency, together with their effects on an FM receiver. Capture ratio, carrier ratios, and residunl signal strength caused by destructive interference are discussed. The reasons behind frequency locked carriers are reviewed, along with the consequences of non-synchronous signals.

Time delay effects on the modulation information are examined, especially as they relate to the composite FM stereo signal and subcarriers. Conclusions are drawn as to the desirability of delay equalized modulation.

Various configurations to transmit both the program material and the frequency locking information are presented. A working system is described giving actual field test results, including the effectiveness of the frequency locking scheme, signal improvement in the primary area of interest, and signal reception in areas of relatively equal carrier ratios. A recommendation for minimum acceptable carrier ratios is presented along with some basic guidelines for the selection of a suitable location for a synchronous FM booster.

7.2 FM SIGNAL CHARACTERISTICS

The FM signal can be defined by the familiar formula found in.

'FM Modulation

$X_c(t) = A_c \text{ Cos } [W_c(t) + B \text{ Sin } W_m(t)]$

Where: A_c = Carrier Amplitude (constant)

$W_c(t) = 2 \pi f_c$ (carrier frequency)

$B = \Delta f/f_m$ (modulation index in radians)

$Wm(t) = 2 \pi f_m$ (modulation frequency)

This formula produces a frequency modulated carrier where the amplitude of the modulation determines the instantaneous carrier frequency, and the modulation frequency dictates the rate at which the carrier frequency is deviated around its nominal center frequency. Note that in FM comprised of only one carrier, the amplitude is constant and the information necessary for detection is contained in the zero crossings.

7.2.1 Adding a Second Carrier

For the purpose of analyzing the effects of a second carrier, the addition of a booster signal can be treated as interference. A second interfering carrier will both amplitude and phase (frequency) modulate an existing, desired carrier. The characteristics of this apparent modulation are given by

Characteristics of an Interfering Signal
Modulating a Desired Signal

$F_m = f_c - f_i$ $\qquad B = A_i/A_c$

Where: f_c = main carrier frequency

f_i = booster (interfering) carrier frequency

A_i = booster (Interfering) carrier amplitude

A_c = main carrier amplitude

Or, in words, an FM receiver detecting two carriers (unmodulated for simplicity), decodes a modulntion tone equal in frequency to the absolute value of the frequency separation between the carriers. Moreover, the modulation index (both AM and FM) is siamply the ratio of the carrier amplitudes. Notice, however, that the modulation index is never more than one, as increasing the amplitude of the interfering signal over that of the original carrier simply makes the carrier the interfering signal to the booster. For FM, B is measured in radians, while for AM, B is the percentage of amplitude modulation produced.

7.3 Synchronous Carriers

This gives rise to the need for synchronizing the carrier frequencies. An analysis of the equation for B (FM) shows, given a fixed carrier ratio (fixed modulation index), an increase in carrier frequency separation is equivalent to an increase in Δf, which for FM is equivalent to an increase in detected signal amplitude FM Modulation Index, Alternate Form

If, given $B = f/F_m$, B is held constant, and F_m is the frequency separation of the carriers, then:

$$f = B * F_m$$

Or, graphically, this phenomenon is shown in Figure 7.

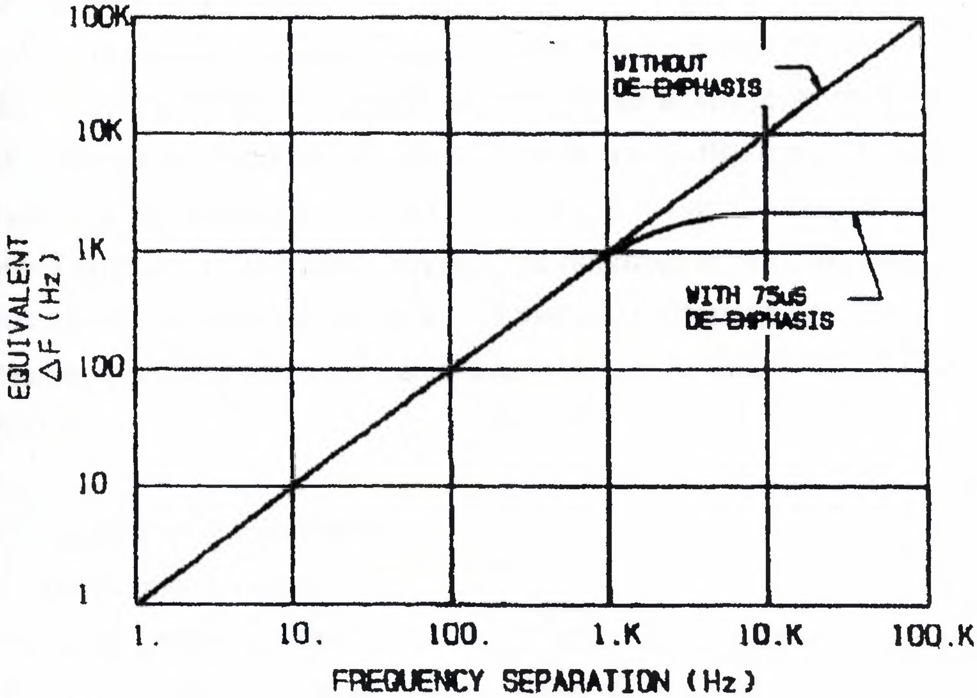


Fig.7 RELATIONSHIP OF CARRIER FREQUENCY SEPERATION TO EQUIVALENT CARRIER FREQUENCY DEVIATION (e=1)

Knowing this, the advantages of frequency locking the carriers becomes obvious. By taking the limit as the difference in carrier frequency approaches zero, two things happen. First, the frequency of the detected tone approaches zero, and the equivalent FM deviation produced by that tone approaches zero. In other words, the interference disappears.

7.3.1 The Resultant Carrler

We are left with a single frequency carrier whose amplitude depends on the relative phase relationship between the two signals at any given reception point. If the signals are in phase and the carrier ratio is one (0 dB), then the resultant amplitude is twice that of either carrier. On the other hand, if the carriers are l80 degrees from each other (out of phase), the net result is zero. Between these two extremes, the resultant amplitude and phase can be derived by

□ Resultant Amplitude of Two Carriers Ar = ([(Ac + Al Cos Wl(t))2 + (Al Sin Wl(t))2]

Where:

Ar = Resultant Carrier Amplitude

Ac = Main Carrier Amplitude

Al = Booster carrier Amplitude

Wl = Angle between Al and Ac

7.3.2 The Resultant Effect on Receivers

Assume for the ,moment we are in a reception area of equal carriers located on a straight tine between the two transmitting antennas, the frequencies are exactly the same, and the signals are additive. Provided that the intomation on each carrier is occurring at the same time, all the conditions for adequate reception have been met.

However, if we were to move 2.5 feet toward either transmitter (roughly equivalent to 1/4 wavelength at 100 MHz), we would now be in an area where the two signals are 180 degrees out of phase, and there no longer be a signal to detect. Notice that we have only moved 1/4 wavelength, yet have actually moved into a null! This is because we have moved 1/4 wavelength away from one transmitter and 1/4 wavelength closer to the other, giving a total 1/2 wavelength change. In a mobile receiver, this phenomenon is virtually identical to the "picket fencing" of multipath, the only difference being the interferlng signal is not reflected, but rather is a duplicate transmission from a booster site.

7.4 SELECTIVE CANCELLATION DUE TO PROPAGATION DELAY DIFFERENCE

However, the distance from the reception point to the main transmitter is 4.9 miles longer than it is to the booster. Assuming the velocity of propagation is that of free space, this is the distance equivalent to 1/2 wavelength at 1 KHz. Therefore, we would again be in an area where there would be complete cancellation of the pilot tone, even though the modulation was equalized at the transmission point and we are in a constructive RF location.

This shows that time delay equalization cannot eliminate cancellation of modulation components 1n equal carrier areas. At best, the use of group delay can move the location of the nulls relative to the transmitters. Great care must be taken to insure the network exhtbits a constant group delay, as non-linear delay can seriously degrade stereo performance, especially stereo separation.

7.4.1 Deviation Calibration

Strictly speaking, if both modulators.are not precisely cnlibrated, a condition of dynamic interference will occur during modulation. In order to understand this phenomenon, consider the following. Two separate modulators are fed identical amplitude, delay equalized sine waves. The level is adjusted to produce a nominal l00x ((75 kHz) awdulation. The first modulator swings the carrier exactly (75 kHz, as predicted, but the second modulator only modulates its carrier (74 kHz (98.67%).

Careful examination shows that the second carrier will interfere with the first in the following manner. Assuming equal carriers in an additive RF location, and starting at time zcro, we have two carriers of exact frequency, producing a single carrier whose amplitude is derived . As we move positively in frequency with the modulation, the carrier frequencies diverge until, at the peak of modulation, the carriers are 1 kHz apart. This produces a 1 kHz FM modulation at a B of 1 (1 kHz deviation) and an AM modulation equivalent to l00% at 1 kHz.

More precisely, the detected interference is actually a frequency sweep from DC to 1 kHz to DC and back to 1 kHz for each complete cycle of modulation applied. The relationship of deviation error (Hz), carrier ratios (B).

Subjectively, this type of interference sounds similar to white noise, but it is only present during modulation. It is also most prevalent during the maximum modulation peaks, as this is the point of maximum carrier divergence with maximum detected loudness.

7.4.2 Correcting the Interference

Both forms of modulation related interference are most prevalent in areas of nearly equal carriers. with "adequate" carrier ratios, both types are effectively eliminated by the capture effect in the FM receiver. It is also important to keep the proper perspective in assessing the importance of these forms of interference. Remember, these are most prevalent in areas where, even without modulation, the carriers are adding and subtracting, tending to make the signal unlistenabte as the receiver location is moved.

In some instances, it may be desirable to add group delay to move a particular null It is also preferable to have the modulators closely aligned. A high quality FM exciter with a carefully calibrated modulation display will provide a very accurate representation of l00% modulation which can be used to closely match the deviation of both exciters.

If possible, simultaneous deviation calibration using Bessel nulls and a spectrum analyzer is strongly recommended. Table 1 lists several modulating frequencies which will cause either a carrier null or a first sideband null Simply inject the same signal into both exciters, preferably through the actunl transmitter link, and adjust the levels until the exciters indicate exactly l00% on the modulation displays. Then adjust each exciter modulation calibration for the desired null on a spectrum analyzer.

MODUIATING FREQUENCY	TYPE OF BESSEL NULL PRODUCED
31,185 Hz	CARRIER NULL (FIRST)
19,470 Hz	FIRST SIDEBAND NULL (FIRST)
13,587 Hz	CARRIER NULL (SECOND)
10,690 Hz	. FIRST SIDEBAND NULL (SECOND)

8,667 Hz	CARRIER NULL (THIRO)
7,372 Hz	FIRST SIDEBAND NULL (THIRD)

TABLE 1 SELECTED BESSEI NUIL FREQUENCIES FOR (75 kHz DEVIATION

7.5 BOOSTER SYSTEMS

Now that we have covered some of the basics of adding a second carrier and the problems associated with it, we can look at some practical ways to interconnect the studio, main transmitter site, and booster site(s). Two main components must be present at the booster station. A way must be found to transmit the station program material, either in the form of composite stereo, or possibly discreet left and right hannels (or mono, if necessary). Composite stereo is preferred, otherwise a second stereo generator would be necessary at the booster. Some form of frequency locking information must also be present. Other interconnections may also be required, such as reinote control and telemetry, but these problems are straightforward and beyond the scope of this chapter.

7.5.1 Using a Radio Link

By far, the most flexible method of interconnection is by the use of a radio link, such as a composite STI between the main transmitter and the booster. This method has several advantages, including high quality transmission, reliability, total signal control and economy. It is also capable of transmitting the frequency reference signal with the composite stereo via subcarrier. In this way, one radio link supplies both the station programning and reference information.

7.6 Frequency Lock

The plug-in interface boards were installed in both the main and booster exciters, and the system was turned on. The system quickly achiered frequency lock. In order to test the accuracy of lock, we drove into the interference area, remotely shut off the booster to verify it was the source of interference, had the studio remove modulation, and listened to the carrier as we slowly drove. The signal was experiencing deep nulls due to the constructive and destructive interferen e between the carriers. We stopped in an additive location, detected by a significant increase in signal to noise ratio of the car receiver, and listened to the received noise floor. The rational behind this test method was, in frequency between the two transmitters, cancel. The result was a suitable change in no time did the signal null. This proved frequency and phase locked, and possessed to reference frequency degradation. If there were even a small shift it would cause the signals to signal to noise ratio, but at conclusively that the system was a high degree of noise inmunity

7.6.1 Coverage Improvement

At this point, a brief outline of the field test location is in order. The test was done in a metropolitan location, with the main transmitter located 18 miles SSW of downtown. Signal reception in downtown was seriously degraded by multipath and a significant intermodulation problem.

The main signal coverage outside of downtown was adequate. The booster was installed in an experimental effort to overcome these problems. Since prior on frequency booster testing had not been done, there was no basis for estimating interference zones or their severity.

The booster was located in the heart of downtown, approximately 2 miles south of the suurce of intermodulation. After the addition of the booster, there was. a significant increase in signal strength in the immediate area, and the multipath problem was virtually eliminated throughout downtown. While the intermodulation problem was not completely overcome, the area of interference was somewhat reduced.

7.6.2 Interference Zones

Outside of downtown, however, a wide area of interference was created. The use of a directional antenna helped to move the areas around, but it was impossible to eliminate them. The problem was much more widespread than expected, and did not seem to follow any of the predicted theoretical equal contour lines. A drive through the interference area with a field strength meter told the story. Carrier ratios as high as 8 dB to as low as 0 dB were measured. The differences in terrain between the main signal path and the booster signal path made the prediction of equal contour or fixed ratio contours difficult.

7.6.3 Carrier Ratios

The end result was a scattering of interference "pockets" with inadequate carrier ratios for quality reception. We drove back toward the booster until the signal was, in our opinion, acceptable, and took a carrier ratio measurement. It was 17 dB! This was surprising, to say the least. The actual threshold of acceptable carrier ratio appears to be both a subjective measurement and varies from radio to radio. The ratio should be smaller for a fixed receiver than for a mobile, but with the great emphasis put on the mobile listener by most stations, this is of little consolation.

CONCLUSION

The accurate prediction of actual audio performance from measured RF bandwidth is a difficult task due to the masking effects of the grid circuit and non-linear nature of the output stage in a single tube transmitter. Carefully controlled testing of RF bandwidth limitation by a passive network tends to show acceptable performance with as little as 800 kHz bandwidth, and little, if any, improvement with more than 1.5 MHz bandwidth. This premise is verified by actual tests on a typical, real world FM broadcast transmitter of less than 1.5 MHz bandwidth.

Therefore, it is concluded that good audio performance can be achieved with as little as 800 kHz bandwidth, and that with 1.0 to 1.5 MHz.bandwidth, excellent audio performance results are obtained, gaining only slight improvement above 1.5 MHz. This optimum bandwidth will produce'outstanding audio fidelity with maximum protection from RF intermodulation potential.

The significance of RF power amplifier circuit topology on FM modulation performance has been identified. The conclusions reached are as follows:

1. RF bandwidth affects audio performance. It is, therefore, necessary to minimize bandwidth limiting canponents in the RF path to reduce performance degradation.
2. Good engineering judgement is called for to balance the trade-offs between modulation performance and imnunity to RF inter-modulation. A bandwidth of 1.0 to 1.5 MHz is adequate for excellent modulation performance while providing protection from RF intermodulation.
3. The design of RF power amplifiers for high quality FM broadcast transmitters requires careful consideration in the choice of input and output circuit topology due to their combined effects on the amplitude and group delay responses. Certain topologies such as broadband input matching and magnetic output coupling result in better overall transmitter performance because their amplitude and group delay responses coincide closely.

4. Measurements taken on a 20 kW FM transmitter showed that tuning the transmitter power amplifier for minimum synchronous AM did not neces5arily result in best modulation performance. Tuning the power amplifier for symmetrical group delay response results in minimum distortion and crosstalk.

5 Equipment manufacturers may provide information on the amplitude and group delay responses of transmitters. This would allov broadcast system engineering to be tailored to particular needs. It would also create opportunities for designing delay equalization networks in the system to compensate for transmitter caused group delays as well as delays caused by the filterplexer and combining system.

The transmitter should be tuned for symmetrical group delay response which results in best FM modulation performance rather than symmetrical amplitude response which results in minimum synchronous AM. Depending on the circuit topology, the tuning conditions for symmetrical group delay response may not coincide with the symmetrical amplitude response.

Simply tuning minimum synchronous AM (symmetrical amplitude response) does notnecessarily result in best FM modulation performance. Best FM modulation performace is always obtained when the system is tuned for symmectrical group delay (time) response.

Most FM transmitters will exhibit a significant increase in synchronous AM when tuned for symmetrical group delay response even though this condition results in best FM modulation performance. The symmetrical group delay tuning point usually does not coincide exactly with the symmetrical amplitude tuning point of minimum synchronous AM and the point of maximum RF power amplifier efficiency. RF power amplifier circuit topologies that exhibit coincidence of symmetrical ampli tude and group delay responses will result in a better overall FM modulation performance. Tests on several FM broadcast transmitters verified that tuning for minimum evenorder harmonic distortion provided the best FM modulation performance with minimumdistortion to the demodulated FM baseband and resulted in symmetrical group delaythrough the transmitter as measured with a network analyzer. These tests also confirmed the FMSIM prediction that group delay response asymmetry causes higher FM modulation distortion and crosstalk than amplitude response asymmetry.

Preliminary testing tends to show the need for 15 to 20 dB of carrier ratio throughout the desired coverage area for quality reception. For most stations considering the addition of a booster, this is not a problem, due to extremely heavy main signal shielding by a natural barrier, such as a mountain. In such locations, the interference zones should be fairly narrow, and will most likely occur in unpopulated areas high atop the mountain. Localized main signal shielding, such as is caused by buildings or small valleys, is not adequate, and the addition of a booster will most likely create more interference outside of the imnediate area than it will fix. IT IS IMPERATIVE TO NOTE THAT THE ADDITION OF A BOOSTER IS NOT A FIX FOR MULTIPATH. IT WiLL. ONLY I IVE THE PROBLEM SOMEWHERE ELSE, AND WILL MOST LIKEIY CREATE MORE INTERFERENCE THAN IT WIIL FIX.

The width of interference zones is difficult to accurately predict, but in general, the better the degree of natural shielding, such as a mountain, the narrower will be the area.

Time delay equalization nnd deviation calibration of the modulation appear to be of limited value in most situations, but may have certain advnntages, depending on the particulars of a given installation. There are a variety of ways to configure a booster system. Some have been described in this paper, but many more ingenious ways remain to be found. The industry is encouraged to pursue different methods so that other economical and reliable systems may evolve.

It is important to remember that the field test results are for one station in one area, and that installntions at other dissimilar locations may produce different results. However, at this time, this is the only basis on which to make predictions. We weleome the findings of other engineers on this subject so that we nay continue to compile an accurate understanding of this new and potentially advantageous field.

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