A Survey of Performance Requirements and Design Techniques for Highest Quality FM Multiplex Reception*

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Reasons for more stringent performance requirements in FM tuners designed for highest quality multiplex reception are discussed. Each of the major functional areas: the front end, the if amplifier, and the multiplex decoder receive attention.

INTRODUCTION

THE introduction of stereophonic FM broadcasting required a new look at FM design practice. Monophonic tuners had been refined over many years of development to a high degree of perfection, and their actual performance requirements could be met fairly easily due to a 15 kc upper limit of modulation frequencies.

This picture changed with the advent of FM multiplex transmissions. Simply adding multiplex-decoding circuits to existing monophonic tuners proved unsatisfactory and could be considered only a temporary measure. The development and field-testing of the new system, prior to its introduction, clearly indicated the need for more stringent performance requirements for FM tuners, designed to take full advantage of the system's capabilities.

In this paper we will first discuss the differences between the two systems and the reasons for more stringent requirements, and then cover the major functional sections, such as front-end, if amplifier and multiplex decoder to show their relative influence on the final performance of an FM tuner designed for multiplex reception of the highest quality.

DIFFERENCES BETWEEN STEREOPHONIC AND MONOPHONIC FM SYSTEMS

The principal differences between stereophonic and monophonic FM systems are:

1. Decreased signal-to-noise ratio of a stereophonic signal as compared to that of the same signal received monophonically.
2. Increased sensitivity of stereo signals to amplitude and phase distortion, resulting from the use of the higher modulating frequencies which are required to carry the stereophonic information.
3. The need for additional circuitry, such as multiplex decoder circuits, in stereo systems.

Differences between the systems result in considerable differences in the design requirements of stereophonic tuners as compared to monophonic ones. This becomes obvious immediately if we consider the disparity in the frequency range of demodulated signals that each tuner is required to handle.

In the monophonic signal, program content is restricted to frequencies up to 15 kc. Consequently, in the design of a monophonic tuner, only the faithful reproduction of frequencies between 30 and 15,000 cps need be considered, and the designer therefore need concern himself only with interference caused by noise, multipath signals, etc., that would result in demodulated frequencies not higher than 15 kc. Actually, due to the use of a 75 μsec de-emphasis network at the detector output, these requirements can be made less stringent, encompassing only frequencies to 7 or 8 kc.

In contrast, the composite stereophonic signal at the output of the FM demodulator contains frequencies up to 53 kc, and no de-emphasis network is inserted between the demodulator and stereo decoder. The 38-kc mixer will therefore effectively transpose not only the stereo difference signal into the audible range, but also any interference which falls into this extended frequency range. The designer of a stereophonic tuner must therefore strive to minimize the distortion of frequencies from 20 cps to 53 kc and to eliminate any audible effect of interferences within this frequency range. Multipath disturbances, for instance, which would have negligible effect on a monophonic signal (because their frequencies lie outside the audible band) can be disastrous to a stereophonic signal. This problem is compounded by

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the fact that the amount of distortion caused by this type of interference increases with frequency.

In addition, the stereophonic demodulation process actually amplifies even minor distortion of the stereophonic sum signal in the frequency range up to 15 kc, so that the need for low distortion for even this portion of the signal becomes more vital than for monophonic signals. The reason for this phenomenon is as follows: harmonics of higher audio frequencies that fall into the passband of the 19-kc amplifier will interfere with the 19-kc pilot signal, causing amplitude and phase modulation. Both types of modulation are superimposed on the 38-kc demodulator signal and result in beat tones of considerable magnitude in the final audio signal.

FRONT-END DESIGN AND SIGNAL-TO-NOISE RATIO

The stereophonic broadcasting standards now in effect result in a signal-to-noise degradation of approximately 23 db for a stereophonic signal as compared to the same signal received monophonically. This figure is of a fairly fixed magnitude and can be altered only to a small degree by tuner design. Thus, the logical approach to the problem of improving the signal-to-noise ratio of the stereophonic signal is to increase its amplitude at the tuner's antenna input and to reduce the noise contributed by the tuner itself.

The most efficient way to increase the input signal is the use of a high-gain FM antenna, such as a dipole with a reflector and one or more directors. This type of antenna has a more or less directional receiving pattern, increasing the amplitude of signals received from the forward direction and attenuating signals arriving from other directions, particularly from the back. This characteristic improves stereophonic reception in two ways: first it provides higher signal levels; second, it eliminates or reduces the reflected portion of the same signal, which arrives with a time delay depending on its length of travel.

The presence of delayed signals results in distortion of the program material. As the transmitter frequency changes, the variation of the phase difference between the primary and the delayed signals produces unwanted amplitude and phase modulation of the primary signal. The phase-modulation component is physically indistinguishable from the desired frequency modulation and appears at the output of an ideal FM tuner as if it were part of the program. On the other hand, the amplitude modulation can be almost completely suppressed by the limiters of the tuner.

The distortion resulting from phase modulation increases with an increasing amplitude of the reflected signal as well as with longer time delay and higher modulation frequencies. The stereophonic signal contains, in the L-R signal, modulating frequencies up to 53 kc, whose phase relationship to each other and to the recovered carrier is therefore more strongly disturbed than for monophonic frequencies with 15 kc as upper limit. This explains the greater susceptibility of a stereophonic signal to distortion due to multipath reception. It also emphasizes the need for an antenna with a strong directional pattern for stereophonic reception in areas affected by this problem.

We mentioned previously that the signal strength must be increased and that the noise contributed by the tuner should be kept as low as possible to improve the signal-to-noise ratio of a stereophonic signal. The well known Nyquist formula defines the total noise power in an amplifying system as:

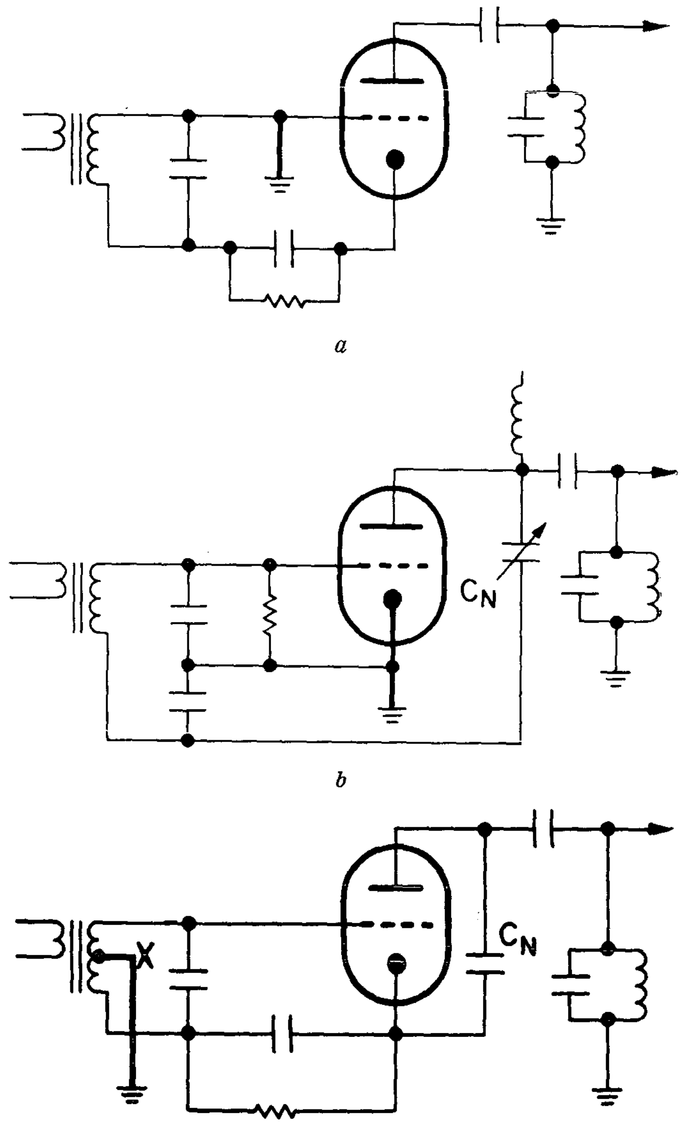

FIG. 1. Radio-frequency amplifying circuits with triodes. *a*. Grounded-grid rf stage. *b*. Grounded-cathode rf stage. *c*. Tapped-coil rf stage. The neutralizing capacitor is represented by C_N.

$$E_n^2 = 4kT\cdot R\cdot B,$$

where E_n = total noise power, R = total noise resistance, and B = bandwidth.

The parameters in this formula that can be affected by front-end design are B and R. The bandwidth B of the front-end section is generally much wider than the if bandwidth, which, in turn, is determined by the requirements of stereophonic reception. Thus R becomes the only variable, containing the combined noise resistances of the antenna, the input circuit and the rf stage, assuming that the latter has sufficient gain so that the noise contributed by the subsequent stages can be neglected.

With a perfect match between the 300 ohm antenna and the 300 ohm transformed input impedance ($R_{ant} = n^2 \cdot R_{sec}$), the minimum possible noise figure of an otherwise noise-free tuner would be 3 db. This condition, called power-match, will result in a voltage standing-wave ratio of 1.0. Although it provides the maximum power transfer and therefore highest gain, power-match does not result in the best

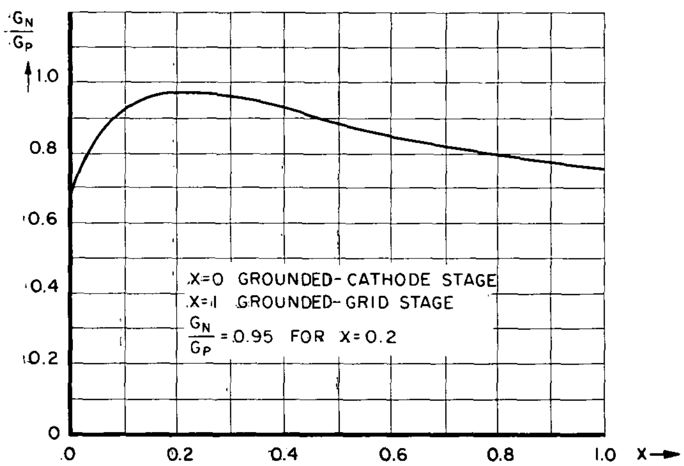

FIG. 2. Ratio of gain with noise-match to gain with power-match *vs* tapping ratio X.

possible signal-to-noise ratio, which can be achieved by increasing R_{sec}. An optimum ratio $a = R_{sec}/R_{ant}$ can be found; this lies between 2.5 and 3.5 for presently used high-gain rf triodes.

The required mismatch of antenna and input impedances has two disadvantages, which although not too serious should be avoided. They are a loss of gain as compared to power match, and a certain amount of reflections of the incoming signal between antenna and input circuits. An ideal circuit configuration would be one which combines power match with noise match and therefore provides highest gain with lowest noise.

Radio-frequency amplification can be provided by a tube working either as a grounded-grid or grounded-cathode amplifier. It can be shown that an input circuit working approximately half-way between these two circuit configurations has the combination of desirable properties mentioned above. Figure 1 shows the three rf-amplyifying circuits.

Figure 1*a* shows a typical grounded-grid rf stage which can be neutralized fairly easily because the tube grid is grounded and acts as a shield between the driving and the driven elements, i.e., the cathode and plate. The main disadvantage of this circuit is its excessive loading of the tuned input circuit. In Fig. 1*b* the cathode is grounded. Here, neutralization is difficult to achieve, since the usual high-gain triodes have relatively high grid-to-plate capacitances in the neighborhood of 1.5 pF. More recent types use internal shields which reduce this figure to approximately 0.5 pF, still too high for stable operation with tuned circuits connected to both grid and plate. Figure 1*c* shows a circuit in which a tap, X, on the input coil is grounded, with grid and cathode remaining above ground. With a particular tapping ratio, noise-match and power-match coincide to give the desired results of highest gain, lowest noise and lowest standing-wave ratio.

Figure 2 shows the ratio between maximum gain with noise-match to gain with power-match in terms of the tapping ratio X. The situation $X = 0$ indicates the operating conditions of a grounded-cathode stage, whereas $X = 1$ represents that of a grounded-grid stage. For both of these circuits, gain with noise-match is approximately 30% less than gain with power-match. With a tapping ratio of $X =$ 0.2, however, noise-match and power-match practically coincide, and more than 95% of the maximum gain is available. The rather flat top of the curve permits some freedom in the choice of the tapping ratio. This can be adjusted to load the input circuit of the rf-stage so that its bandwidth becomes wide enough to pass all frequencies within the FM band. This circuit can therefore be fixed-tuned to the center of the band, leaving the third gang of a 3-section tuning capacitor available for a double-tuned plate circuit. This arrangement has higher selectivity and is more efficient in suppressing frequencies outside its bandwidth than the common arrangement of a tuned circuit at the grid and plate. Neutralization of the single-triode rf-stage with a tapped coil can be achieved with the bridge circuit shown in Fig. 3.

Assuming that the coil is tapped and its electrical center ($X = 0.5$), the plate-grid and plate-cathode capacitances must be equal to achieve neutralization. If one is lower than the other, an external capacitor C_n can be added.

In our designs we have replaced previously-used cascode circuits with an FM front-end using a single neutralized

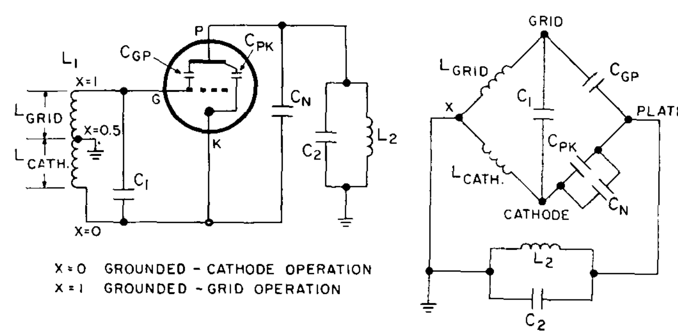

FIG. 3. *Left:* Radio-frequency amplifier stage with single triode and tapped-coil circuit. *Right:* equivalent circuit of the neutralization bridge.

triode as an rf-stage with a tapped-coil circuit. It has been found that a single triode permits a slightly better noise figure than a cascode stage.

In a cascode circuit, a grounded-cathode triode works into the low-input impedance of a grounded-grid triode. The gain of the first stage is therefore very low, on the order of 0 db or slightly higher, eliminating problems in neutralizing. The gain of the grounded-cathode stage is consequently not high enough to prevent the noise contribution of the second grounded-grid stage. A neutrode circuit using a single triode

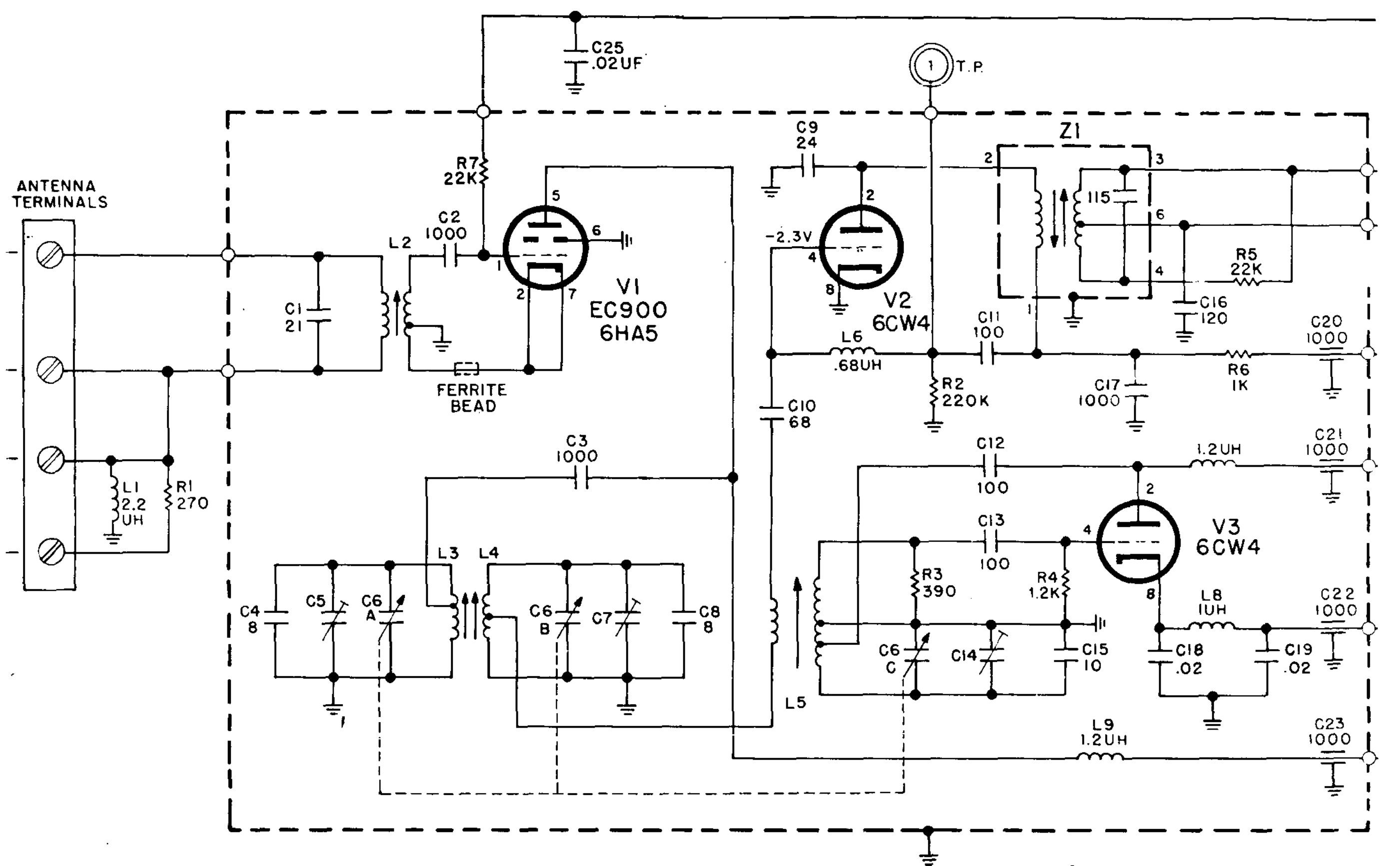

FIG. 4. Circuit diagram of the FM front-end.

has slightly less gain than a cascode (assuming triodes of equal parameters); however, it yields a noise figure which is approximately 0.5 to 0.8 db lower.

Figure 4 shows the circuit diagram of a complete FM front-end with a single triode used as an rf-amplifier, two Nuvistors used as mixer and oscillator, and three tuned circuits, two of which work as a double-tuned filter between the rf stage and the mixer.

Summarizing, then, the following objectives have been achieved in the front-end: *1.* Reduced front-end noise obtained by means of a noise-matched input circuit and use of a single triode as rf amplifier. *2.* Low standing-wave ratio maintained with a circuit that combines power and noise match. *3.* Increased selectivity and therefore increased rejection of spurious responses with a double-tuned plate circuit.

DESIGN OF THE IF-AMPLIFIER

The second main difference between stereo and mono, as explained previously, stems from the need for higher modulation frequencies in transmitting the stereophonic signals. This results in more stringent performance requirements for the linear and nonlinear sections of the if amplifier as well as the detector circuits.

The linear if amplifier sections must provide the selectivity required to sufficiently suppress stations in adjacent and alternate channels. The tuned circuits used for this purpose should be designed to have sufficient bandwidth and only a very limited influence on the amplitude and phase of the received signal.

We will first discuss the effect of limited bandwidth on amplitude and phase-distortion, and then delineate requirements of an if amplifier designed to minimize these effects.

Ideal amplification of the composite and SCA signals would require a linear amplitude characteristic for the if curve. A decrease in amplitude with frequency will result in *audio distortion.*

The spectrum of an FM-modulated signal is theoretically infinitely wide. For practical purposes, however, it is sufficient to design for a bandwidth which includes all sideband frequencies having 1% of the unmodulated carrier's amplitude. The bandwidth then required can be approximated by:

$$B = 2(\Delta F + 2f_0),$$

where ΔF = maximum system deviation and f_0 = highest modulation frequency.

For a monophonic signal we arrive at 210 kc, and for the composite signal without SCA at 362 kc. The bandwidth required for the stereophonic signal, however, can be made smaller because the resulting distortion is determined not only by bandwidth but also the modulation factor $m = \Delta F/f$. With a maximum system deviation of 75 kc, the modulation index, for the highest audio frequency of 15 kc used in monophonic transmission, is 5.

The highest frequency of the stereophonic L-R signal, when a 15 kc audio signal modulates the 38 kc carrier, is 53 kc. Of the maximum signal deviation of 67.5 kc only 50% is available for the L-R signal. As an amplitude-modulated signal with both sidebands transmitted, the total maximum deviation is reduced to half of this figure, or approximately 17 kc for the upper sideband frequency of 53 kc. The resulting modulation index of 0.32 requires only the inclusion of the first and second pair of sidebands for a total bandwidth of 4×53 kc $= 212$ kc.

Allowing some tolerance, a bandwidth of 240 kc has been found to be sufficient and practicable to achieve the selectivity required to suppress stations in the adjacent and alternate channels.

A second defect resulting from amplitude roll-off is *crosstalk*.

Attenuation of higher modulation frequencies changes the relative amplitude of the upper and lower sideband frequencies and their level in relation to the L + R signal. Any change in amplitude disturbs the balance of the original signal and reduces separation of the recovered L and R information. The quantitative influence of this roll-off can be found as follows:

The L and R signals at the stereo modulator are

$$A(t) = A \sin \omega_a t; \quad B(t) = B \sin \omega_b t;$$

where A and B are the amplitudes of the L and R signals.

We temporarily disregard phase distortion and consider only A and B. Assuming that after demodulation and matrixing the $A - B$ signal is reduced in amplitude by the factor d, we can write

$$(A+B)+d(A-B)=(1+d)A+(1-d)B \text{ and}$$
$$(A+B)-d(A-B)=(1-d)A+(1-d)B.$$

The L and R channels contain not only A and B, but also portions of the signal from the opposite channel.

Stereo separation S related to factor d can now be expressed as

$$S = 20 \log[(1+d)/(1-d)] \quad \text{(db)}.$$

This relationship is shown in Fig. 5. It can be seen that

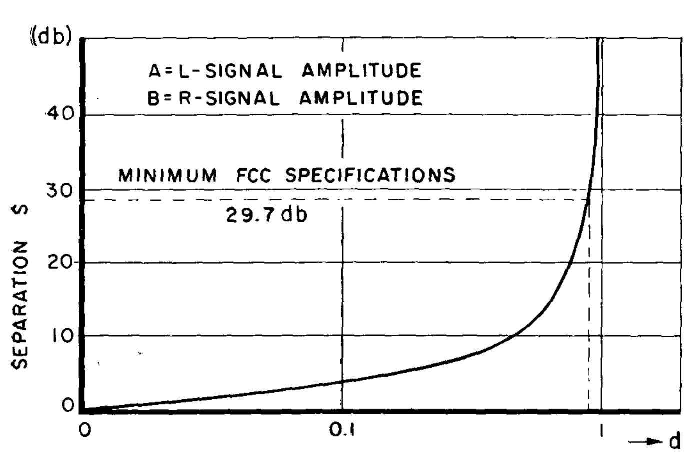

FIG. 5. Separation between L and R signals as a function of the factor $d = (A-B)/(A+B)$.

separation decreases rapidly with even minor deviations of d from unity. To meet minimum FCC specifications, d must be 0.94 or higher. To a certain extent, the loss of separation due to amplitude roll-off can be reduced in the decoder section either by attenuating the sum signal to $d(A+B)$ or by crossfeeding both channels.

Phase Distortion. The phase characteristics of the if section and demodulator can cause nonlinear distortion of the FM signal. When the phase-angle ψ between input and output is not proportional to ω, then the delay time $\tau = d\psi/d\omega$ will not remain constant for all frequencies of the stereophonic signal. The amount of change in the delay time

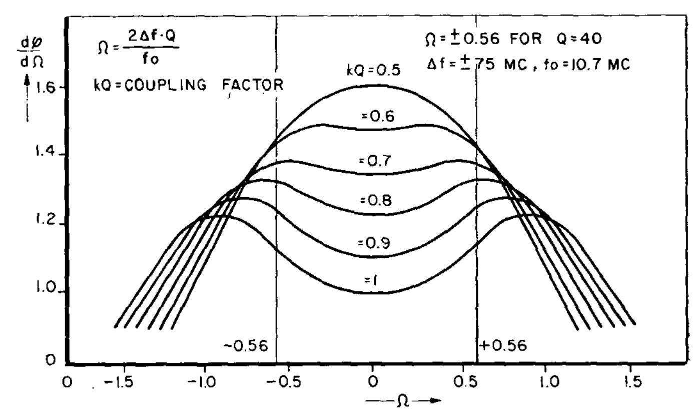

FIG. 6. Phase-frequency characteristic *vs* normalized deviation for a double-tuned if filter with coupling factor kQ.

will determine the amount of phase distortion. An FM-modulated wave is particularly sensitive to phase distortion resulting from the nonlinear phase characteristics of the if section, since any frequency shift of a wave is accompanied by phase shift and conversely.

Distortion will result from the nonlinear characteristics of the if amplifier as follows:

1. When the carrier frequency is not tuned to the center of the if curve or when the curve has an unsymmetrical shape, even harmonics, particularly a strong second harmonic, will result.

2. Even if tuned to the center of a symmetrical if curve, the signal will still be distorted if the time delay is not constant for all frequencies. In this case, however, uneven harmonics, particularly the third, will prevail.

Computing the total permissible difference in time-delay, $\Delta\tau$, for maximum deviation and for a maximum distortion of perhaps 1%, we will arrive at fairly low values. An example, using the usual double-tuned mutually-coupled if filters will confirm this.

Since the coupling factor kQ greatly affects the final figures, we must first determine its optimum value. Figure 6 shows $d\psi/d\Omega$ on the Y-axis and the normalized deviation Ω from the center frequency on the X-axis. As we can see, a coupling factor kQ of 0.7 (or 70% of critical coupling) shows the least change of $d\psi/d\Omega$ within the if passband (marked by the two vertical lines). However, in practice it was found that a minimum value of 0.8 is preferable to achieve the required bandwidth. Using 0.8 for the coupling factor, we first compute the actual Q-factor of the filters used, then the phase delay time for the 10.7 mc center frequency and for frequencies 75 kc higher and lower. The delay time τ of a double-tuned filter can be expressed as

$$\tau = (2Q/\omega_0)\cdot(d\psi/d\Omega),$$

where $f_0 = \omega_0/2\pi = 10.7$ mc and $\Omega = (2\Delta f\cdot Q)/f_0$ (normalized frequency deviation). The quality factor Q must be chosen to meet the previously established bandwidth requirements, considering the number of filter stages used and their relative coupling. Under these conditions Q should be 40 for each of three double-tuned filters. Using these figures we find $d\psi/d\Omega = 1.22$ at the 10.7 mc center frequency and 1.29 at a frequency $\pm$ 75 kc away.

The corresponding delay times are 1.46 μsec and 1.55 μsec respectively, i.e., $\Delta\tau = 0.09$. The resulting second-harmonic distortion, which can be derived from the formula

$$d_2 = \tfrac{1}{2}\,\omega_m\cdot\Delta\tau,$$

is 0.47% for a frequency of 15 kc.

This distortion figure appears to be high, particularly for a single double-tuned filter. It should be considered, however, that we used an extreme case, with highest frequency of the monophonic signal and a maximum deviation of $\pm$ 75 kc. For a L-R frequency of 53 kc and a Q of 40, we arrive at a difference in time delay of 0.03 μsec and 0.48% distortion. The time delay differences for all filters must be added to arrive at the total distortion figure. Several possibilities exist, however, to reduce the distortion contributed by the if amplifier, first by further lowering the Q-factor of the tuned circuits and then by compensating the phase characteristics of one filter by the opposite characteristic of a second one. This can be done, for instance, by using filters with undercritical and overcritical coupling. The upper and lower curves in Fig. 6 representing different coupling factors, explain this possibility. This principle, however, should be applied cautiously, as incorrect alignment of one of the filters will overcompensate the if amplifier and thus greatly increase the resulting distortion.

To maintain the established parameters of an if amplifier with regard to frequency response, phase characteristics, and selectivity, all tubes in this section should operate as straight amplifiers regardless of the antenna signal level. To prevent the possibility of overloading one or more stages, AGC should be applied to the rf stage, and in most cases also to the first if amplifier tube. A negative AGC voltage will reduce the transconductance of this tube and at the same time change its dynamic grid capacitance. This in turn can cause harmonic distortion by detuning the secondaries of the filters to which the grid is connected. A very loose coupling between tube and filter can alleviate this condition, but only a compensation of the capacitance change through current feedback can practically eliminate this problem. An un-bypassed cathode resistor of proper value will reduce this change to negligible values.

The preceding discussion covered only the linear or selective section of the if amplifier. In addition, the limiters and the detector must be designed to meet the more stringent requirement of stereophonic reception.

1. The unwanted AM modulation of the FM signal resulting from multipath reception, other interferences and from a rounded if response curve should be fully suppressed. Practical considerations require AM suppression of at least 40 db.

2. The time constant of the limiter should be made sufficiently small to enable it to suppress the higher AM modulation frequencies encountered during multipath reception of a stereo-modulated carrier wave. A time constant of 2 to 3 μsec will meet this demand.

3. Most limiters work satisfactorily in suppressing low AM frequencies. Their efficiency, however, seems to decrease with higher AM frequencies. Measuring the AM rejection factor of most limiters shows that the suppression of lower AM frequencies as measured at the detector *output* increases with increasing FM signal amplitude. For higher AM frequencies and also for increasing input signal strength, however, the AM suppression will decrease again after a short increase. This happens even as the content of AM in the FM-modulated signal, as measured at the ratio detector *input*, decreases steadily. Analyzing this behavior, it was found that AM frequencies can create a fairly large amount of phase modulation within the limiter stages. Converted to FM-modulation, the resulting output voltage at the detector increases with frequency, explaining the apparent decrease in suppression of higher AM frequencies.

Phase modulation due to detuning of the grid circuit at the limiter as a source for this behavior can be ruled out since the un-bypassed resistor in the cathode prevented it. However, positive feedback from the limiter plate via C_{gp} to the grid circuit can create undesirable phase modulation if this stage is not perfectly neutralized.

The requirements imposed on the FM-AM converter used in stereophonic tuners will be covered only briefly.

1. A flat detector output voltage *vs* modulation frequency characteristic will maintain phase and amplitude relationship between upper and lower sidebands and between them and the L + R signal. Amplitude roll-off would result in unequal sidebands, creating distortion and loss of separation. The above requirements are met when the detector, represented as a generator with an output resistance R and a parallel capacitance C, has a time constant of 2 μsec or less.

2. The linear portion of the *S*-curve should be made wide enough to demodulate all frequencies with the lowest possible distortion. This particular requirement is met by a peak-to-peak separation of 600 kc. Even *wider* bandwidth is required to take full advantage of the capture ratio effect, one of the most valuable assets gained through FM modulation.

The fact that an FM signal can fully suppress an interfering signal of the same frequency and lower amplitude can be used to increase the dynamic selectivity of FM tuners and to reduce the effects of ignition noise and multipath interference. The amplitude ratio between the desired and undesired signals required to suppress the lower amplitude signal to a given degree is called capture ratio, and its value is determined mainly by the bandwidth of the limiter section and the detector. The linear or selective part of the if amplifier can also affect the relative level of the FM signal and the interference, depending on their momentary position on a rounded if response curve. However, the previously established requirements of a linear frequency response for the if amplifier will minimize the influence of its selective portion.

The bandwidth required for the limiter and detector depends on the maximum frequency deviation and the desired capture ratio. It can be expressed as

$$B = [(1+a)/(1-a)] \cdot 2\Delta F,$$

where a is the maximum permissible amplitude ratio between undesired and desired signal for a given amount of attenuation. With a deviation of 75 kc and a capture ratio of 2 db, a limiter and detector bandwidth of approximately 1.35 mc is required (assuming that the linear section does not contribute to the capture ratio).

Again, we can summarize the main requirements on an if amplifier designed for high-quality stereophonic reception:

1. Bandwidth should be at least 240 kc to maintain amplitude linearity to the highest modulation frequencies of the stereophonic signal.
2. There should be minimum variation of the phase-frequency characteristic within the required bandwidth, as can be achieved by the proper values of Q and coupling factor for the tuned if filters.
3. The symmetrical shape of the if curve should not be distorted as the result of positive or negative feedback.
4. Detuning of the if curve and parasitic phase modulation of higher frequencies with limiting or the use of AGC should be avoided.
5. The minimum value of selectivity required for adjacent or alternate channel suppression should be maintained regardless of the antenna signal levels.
6. The bandwidth of the limiter section and of the detector is to be determined by the desired value of the capture ratio.
7. The detector should have a flat output voltage *vs* modulation frequency characteristic. When represented as a generator, it should have a time constant of 2 μsec or less.

THE DECODER

The last remaining section of the FM tuner is the multiplex decoder. Its performance requirements have been dealt with extensively in previous papers, and the main points will only be summarized very briefly. They are:

1. The 19-kc amplifier should meet the requirements of sufficient gain and selectivity as well as long- and short-term stability.
2. A constant phase relationship between the L-R signal information and the recovered 38-kc signal should be maintained regardless of the amplitude of the synchronizing signal.
3. The SCA filter should not affect the relative phase for frequencies of the composite signal.
4. The output circuit should contain a lowpass filter which will sufficiently attenuate the 19-kc, 38-kc and L-R sideband frequencies.
5. For ease of operation, a device would be desirable which automatically switches the decoder section to the monophonic or stereophonic mode of operation depending on the type of signal transmitted. This device should not be affected by noise, distortion or other external disturbances.

CONCLUSION

We have established that each section of a high-quality FM tuner must meet the more stringent performance requirements imposed by the FM multiplex system. Careful attention to these important design considerations will result in an FM tuner capable of bringing to the FM listener the full enjoyment of high-quality stereo programs.

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