SERRASOID

Design data for an improved four-tube phase-shift type modulator that initiates 100-percent modulation with noise 80 db down and 0.25 percent harmonic distortion in broadcast service. Low relative cost suggests potentially greater utilization of the educational frequencies. Variations of the basic circuit open new fields of application

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THE development of a simple f-m modulator has been one phase of a broad program to enlarge the technical horizons of f-m broadcasting. In particular, it was aimed at providing one solution to the problems of relay and chain broadcasting. Such service requires that the noise background and distortion be very low in the individual links so that the final signal may still meet the relatively high standards required for any f-m broadcasting system. Such chain systems have been operated satisfactorily using available equipment, but it cannot be said that, in the more extensive chains, the limiting noise rests with the audio facilities at the origin. This latter condition has always been regarded as a minimum requirement of a really good f-m broadcast setup.

Careful examination of the problems in a reasonably extensive chain yields the conclusion that an 80 db ratio of 100-percent modulation to noise in the modulator would be satisfactory. In addition, a maximum figure of 0.25-percent harmonic distortion for 100-percent modulation with single tones from 50 to 15,000 cycles was set as a correlative objective. Since a practical modulator involves accessory circuits such as an audio amplifier, which can be expected to make some definite though small contribution to the numbers above, the actual net requirements on the modulation process are somewhat more severe than the overall figures. It is evident that such performance will also be of significant application in a single f-m broadcast setup, apart from the special question of relaying.

Means of generating frequency-modulated currents fall into two general classes, the reactance-modulated type, and the phase-shift type. In the first, the frequency of an oscillator is caused to vary linearly with modulation through the agency of a reactance tube or its equivalent, which is an integral part of the frequency-determining circuit. Because of the modulation and linearity requirement such an oscillator in general is not stable enough for broadcast service. Automatic frequency control is therefore employed. In the phase-shift type of modulator the frequency of the carrier oscillator is not varied, and therefore a stiff control such as a quartz crystal can be used to secure the desired stability, which then is completely independent of the modulation process. Modulation of the frequency in such a system is secured by varying the phase of the frequency-stabilized wave. The frequency will be deviated from its controlled value only during the time the phase is changing, and the deviation, other things being equal, is proportional to the rate of change of phase.

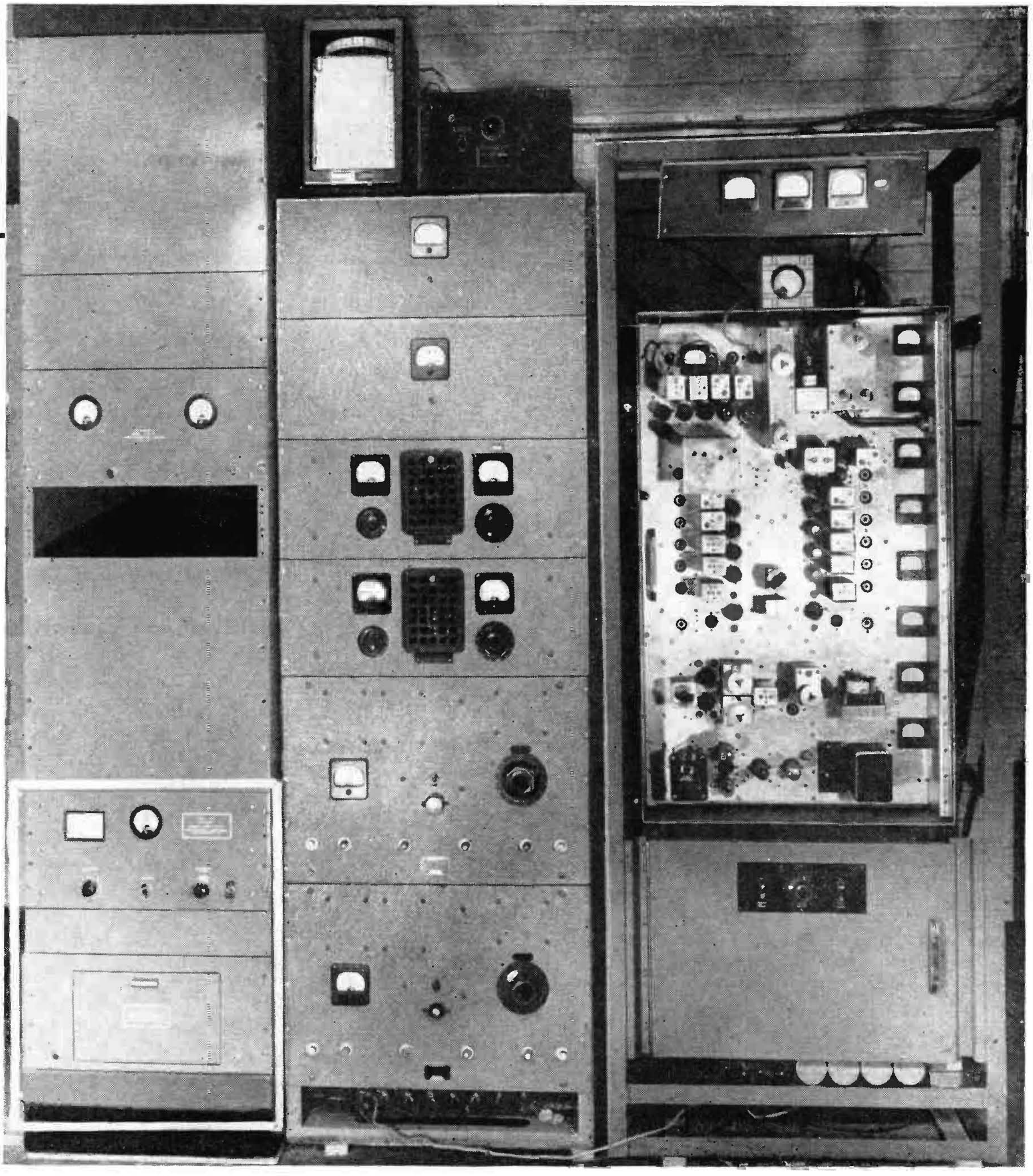
The Serrasoid is the latter type. Although it is capable of broader

The first successful method of producing frequency modulation was the phase-shift method. Despite certain shortcomings in inherent noise, distortion at the lower modulating frequencies, and a tendency of the center frequency to drift, it carried the burden of launching the f-m system successfully.

- The invention of the double channel modulator, which was brought to a high degree of perfection through the work of John Bose, eliminated these difficulties. It, however, had the commercial disadvantage common to all frequency modulators of requiring a large number of tubes. This disadvantage is not of much importance in transmitters of powers above 1 kw, as the cost of the modulator then becomes a relatively small part of the total. For transmitters of low power, however, the modulator becomes a major item. Herein lies opportunity for great improvement.
- I have always felt that the phase-shift method of producing frequency modulation would be the surviving method and that someone some day would overcome its greatest weakness by finding the means of increasing the initial phase-shift without compromising any of the requirements of distortionless noise-free f-m.
- This James R. Day has done. Not only has he done it without compromise, but he has in fact improved performance to hitherto unattained levels.
- The significance of this development is that by its simplicity and reliability it has opened up all sorts of new broadcasting possibilities. One can visualize the operation of unsupervised transmitters of a few watts power, controlled from pulpits, schoolhouse assembly halls, and similar places, the transmitter requiring no more attention than the common, everyday public address system.
- The invention has opened up some amusing possibilities. If, as seems likely, the Serrasoid becomes the accepted method of producing frequency modulation, the phrase-makers who have dubbed the phase-shift method the "indirect method" will find themselves in an awkward situation. Some of us have lived long enough to recall the days when the automobile was referred to as the "horseless carriage."

—E. H. ARMSTRONG

F-M MODULATOR



Size comparison between the Serrasoid modulator (outlined in white) and the original Dual-Channel modulator at the right. Center rack and upper section of left rack are used for other equipment. Photograph taken at the Armstrong f-m broadcast station W2XMN-W2XEA at Alpine, N. J. where the new modulator has been in service for six months

application, the numbers involved for the f-m broadcast case provide the clearest illustrative material. As noted above, frequency deviation is proportional to rate of change of phase. For sinusoidal modulation this is simply expressed by saying that the peak frequency deviation is equal to the product of the peak phase shift and the modulating frequency. The new circuit is conservatively capable of a peak phase shift of ± 150 degrees, but ± 90 degrees or $\pm 1\frac{1}{2}$ radians is used as the basis for 100-percent modulation at 50 cycles. For $1\frac{1}{2}$ radians and 50 cycles the peak deviation therefore will be ± 75 cycles. Since 100-percent modulation in f-m broadcasting is a deviation of $\pm 75{,}000$ cycles, a frequency multiplication of 1,000 is indicated. Actually, 972 is used since it can be factored into a convenient assortment of doublers and triplers. In all that follows we shall discuss a modulator for a frequency of 97.2 megacycles which starts at a base frequency of 100 kilocycles.

Figure 1 is a schematic diagram of the essential parts of a complete broadcast Serrasoid. Audio amplifiers and frequency multipliers have been omitted since they are conventional and employ small standard type tubes. Tube V_1 is a pentode oscillator controlled by quartz crystal Y. The crystal operates very close to its series resonant frequency. The net reactance of the crystal arm may be conveniently varied by a series capacitor for fine frequency adjustment of about ±0.005 percent. This crystal is oven controlled in the broadcast case to a net stability of ±0.0002 percent, which is also the stability of the final carrier frequency. The operation of the oscillator is such that plate current is drawn only during a small part of the cycle. Negative going pulses shown in Fig. 2A are generated at the plate of V_1. These pulses are differentiated by C_3, R_4, and grid-cathode conductance of V_{2A} to yield still shorter pulses several times the cutoff voltage of V_{2A}. The corresponding short positive pulses at the plate of this latter tube are bottom clipped (to clean the base line) by cathode follower V_{2B}. Resistor R_7 is selected so that this tube is biased beyond cutoff between pulses by the automatic grid bias of C_4 and R_6. The pulses at the cathode of V_{2B} appear as shown in Fig. 2B. The two halves of V_2 perform the functions of a single pentode that might have been used in the same place, with the additional advantage that the final waveform is developed in a lower impedance than is practicable with a pentode.

Linear Sawtooth Wave

According to the numbers of the illustrative case these pulses recur at a rate of 100 kilocycles, that is, corresponding points or events on consecutive pulses are 10 microseconds apart. Tube V_{3A} constitutes a nonoscillatory sawtooth generator timed by the pulses from V_{2B}. The slowly increasing portion of the sawtooth has a slope corresponding to the charging of C_7 through R_{10} to the relatively steady voltage at the junction of R_9 and R_{10}. This period coincides with the time between pulses at the grid of V_{3A}, cutoff bias having been developed on C_5 by previous pulses. The quickly decreasing portion of the sawtooth occurs at the time of positive pulses on V_{3A}, when C_7 is discharged nearly to cathode potential by the plate-cathode conductance. In round numbers the discharge point is about 5 volts from cathode or ground potential and R_{10} and C_7 are adjusted to give a rising rate of about 4 volts per microsecond to the increasing portion of the wave. As will be shown the whole linearity of the modulation process depends on the straightness of this sawtooth wave. In its simple form, it would have too much exponential curvature to be useful. This condition is corrected by the bootstrap connection comprising the cathode follower V_{3B}, R_{11}, C_6, and R_9. The normally constant voltage at the positive end of R_{10} has superimposed upon it the rising voltage on C_7 so that the drop on R_{10} and hence the charging current is maintained practically constant. Resistor R_9, as in other bootstrap applications could be a diode with its anode at plate supply potential, but for the voltage magnitudes involved here the resistor is more than adequate. The d-c voltage at the junction of R_9 and R_{10} is about +190 volts for a B+ value of 250 volts.

Pulses are Frequency-Modulated

The sawtooth wave thus developed is directly coupled to the grid of V_{4A}. This tube is cathode biased by its plate current so that conduction begins when the sawtooth is about half way up; the passage from the beginning of plate current flow to grid current consuming about 0.25 microsecond. Because C_8 is large and holds the bias constant during the sawtooth period, grid current stops the charging of C_7, and the latter half of the sawtooth rise is clipped. The resulting waveform is shown in Fig. 2C the dashed line indicating the waveform without the direct coupling to the grid of V_{4A}. Thus, the plate current of V_{4A} flows only during the

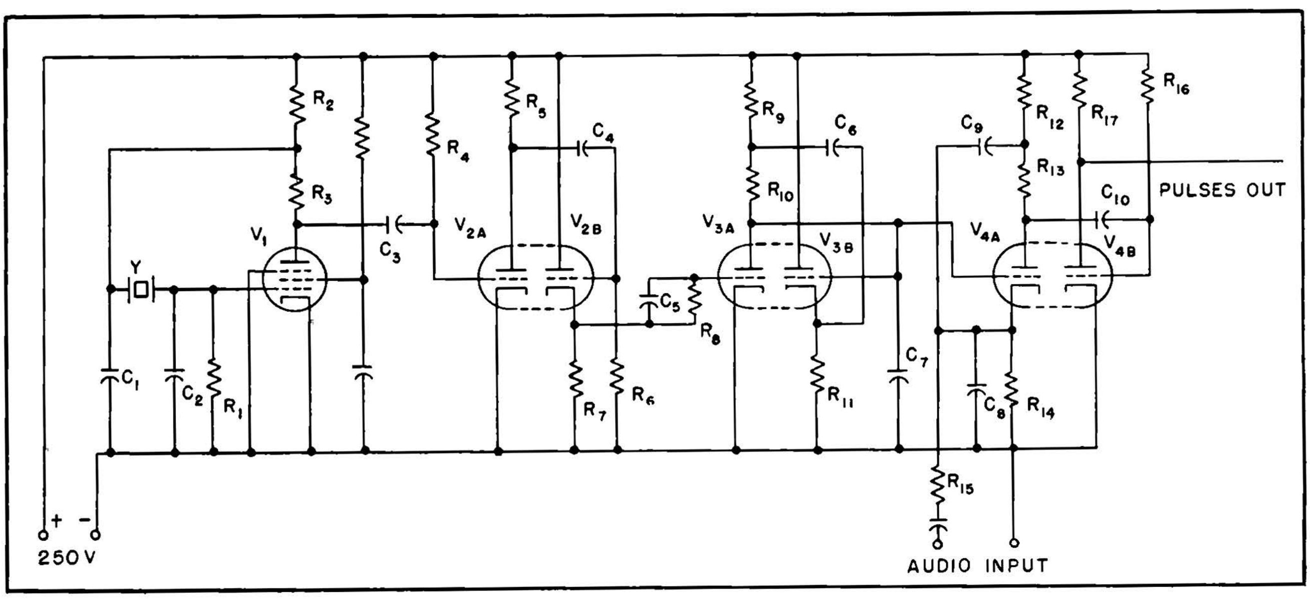


FIG. 1—The modulator proper showing the crystal oscillator, clipper, sawtooth generator and bootstrap cathode follower, and f-m pulse output tubes. The frequency multiplier stages that follow are conventional

latter half of the sawtooth wave. If the bias for V_{4A} is varied, the leading edge of this current pulse will vary in time or phase, an advance resulting from a lowering of the bias and a retardation from an increase. It is in this way that phase modulation in the unit is accomplished.

Audio or program is applied at the indicated terminals. Values of R_{15} and C_8 are so proportioned that for constant audio input amplitude versus frequency, the resulting amplitude at C_8 is inversely proportional to audio frequency over the range upward from 50 cycles. This circuit is included so that the peak phase shift shall be inversely proportional to modulating frequency and the resulting frequency response of the frequency modulation shall be flat. The function and the network are the familiar corrector present in all phase-shift type frequency modulators. In order that at 50 cycles the phase of the pulse edge be shifted $\pm 1\frac{1}{2}$ radians, approximately 50 volts rms is required at the input to the corrector. In the complete modulator a two-stage amplifier provides the gain to raise the standard input of ± 10 dbm to this level. Since feedback is used in this audio amplifier to provide linearity, the effective modulation sensitivity is also stabilized to a marked degree. This sensitivity depends only on the audio gain and the stability of R_{10} and C_7, and ordinarily is stable to within 1 percent for the standard ranges of temperature, line voltage, and tube changes.

Figure 2D illustrates the waveform at the plate of V_{4A}, the dashed lines showing the extreme positions of the leading or negative going edge during 100-percent modulation at 50 cycles. For 100-percent modulation at 100 cycles the excursion is one half that shown, and so on. This wave is differentiated by C_{10}, R_{10}, and the grid cathode conductance of V_{4B} so that the latter is cut off for a short time each cycle beginning at the leading edge. The resulting positive-going pulses at the plate of V_{4B} are shown in Fig. 2E. These pulses are frequency modulated approximately ± 75 cycles at 100-percent modulation. They are applied to the grid of the first of a string of frequency multipliers. The plate

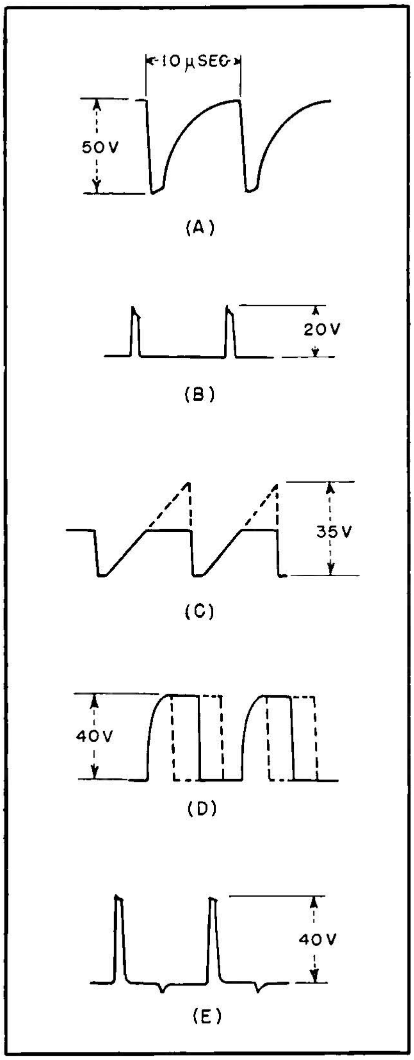


FIG. 2—Waveforms, oscillator to output

loads of this and subsequent multipliers are resonant at the various harmonics, and therefore, involve only sinusoidal c-w currents. In the broadcast version these multiplications are 3, 3, 3, 3, 2, 3, and 2, for a total of 972 times, yielding a carrier frequency in this illustration of 97.2 megacycles with a deviation of ± 75 kilocycles at 100-percent modulation.

Circuit Design Factors

Before proceeding to a discussion of distortion and noise in a system of this sort several salient features may be pointed out. First, in common with all phase-shift modulators, there is no interaction whatever between the functions of modulation and carrier-frequency control, and the final stability is exactly that of well engineered crystal control. Exclusive of the frequency control the modulation process is accomplished in three standard receiving type tubes operating under cutoff to saturation or cathode follower conditions. As a result the process is remarkably independent of tube changes or aging. There are no resonant circuits and no reactances. Largely to eliminate the commercial tolerances of resistors and capacitors, C_3, C_7, C_{10}, and R_{14} are factory adjusted, and thereafter no adjustments even of a maintenance nature are necessary, except after outright component failure. Tubes V_1 through V_4 drain about 20 milliamperes at 250 volts.

Possible Variations

An interesting aspect of the development of this modulator lies in its apparent simplicity. Until certain special factors were fully appreciated performance was indifferent and the simultaneous attainment of low distortion and low noise hardly seemed practical without considerable elaboration. A good many detailed variations from the sample circuit shown are operative, and some yield high performance. But without the observance of certain principles, design can be surprisingly difficult. The important rules affecting linearity and noise are enumerated below.

Having selected the sawtooth waveform as the basic timing or phase-shifting mechanism, it developed that linearity could not be preserved if it was amplified or caused to appear as a current variation in a plate-loaded tube, no matter how attractive such a step may have appeared at first. Other means of straightening the sawtooth beside the bootstrap arrangement shown are entirely practical provided the sawtooth waveshape as such is not amplified. In particular, in the modulation process the tube performing the timing, V_{4A}, cannot carry currents of sawtooth shape and still preserve linearity in the timing process. It was found also that the amplitude of the current pulses in V_{4A} should be constant during the modulation cycle. To insure this condition the plate supply voltage is maintained constant by C_9. The supply voltage is low, about 30 volts, giving a small cutoff voltage.

Noise arises in such a system in the form of random variations in the time of occurrence of corresponding events in consecutive cycles. Such timing variations ordinarily are the result of superposition of noise voltages on the desired wave-form. The noise voltages originate either in tube current variations or as Johnson noise in resistors. The effects of both kinds of noise are reduced by increasing the time rate of change of voltage in the sides of the pulses, and by maintaining low circuit impedances at certain points. For instance, impedances controlled by R_3, R_7, and R_{10} are in a position to contribute to the residual modulator noise unless maintained below values appropriate to the pulse amplitudes appearing across them. This is another way of saying that the circuit bandwidth should be as great as possible so that the pulse rise-time is short. Noise originating from uniformly distributed random voltage variations causes frequency modulation noise with a triangular distribution spectrum, extending linearly up from zero at zero modulating frequency. For the band up to 15,000 cycles the integrated noise power from a given resistance is approximately 44 db greater than would be the case for a flat noise spectrum. The 75 microsecond de-emphasis in the f-m receiver reduces this effect by 13 db. The reduction factor is different if the original noise is other than triangular. For instance, Johnson noise in R_{10} is modified in its spectrum by C_7 before it can phase modulate pulses determined by the sawtooth. It is a straightforward matter to show by calculation that if the linearity were secured without the bootstrap or its low-voltage equivalent, that is, by making the supply voltage very high, the noise generated by the necessary large resistor would be excessive by a considerable factor. Thus it comes about that the bootstrap or its low voltage equivalent is uniquely essential to securing simultaneously low noise and low distortion. By similar reasoning it can be shown that the lowest noise is obtained when the corrector capacitor C_8, is directly at the modulator cathode. If the corrector were to be located at a lower level in the audio section, tube and Johnson noise originating after it would have a 31 db handicap and with practical tubes and circuit constants, this effect would be insurmountable. The possibility of noise phase modulation in the first tube after V_4 is minimized by making this a frequency multiplier so that the noise deviations are multiplied by a smaller factor than those originating in V_4 and earlier.

Performance

The general performance of the Serrasoid system in the particular case shown, and following the design rules noted can be summarized as follows. The linearity of the phase-shift process is readily made to be equivalent to less than 0.1-percent f-m distortion for peak phase shifts of ±135 degrees. It should be noted that nonlinearity in the phase-shift process results in f-m distortion proportional to the order of the harmonic generated. Thus 1 percent third harmonic expressed as distortion of the phase shift is equivalent to 3-percent distortion measured as frequency modulation. In the commercial f-m broadcast modulator the distortion is largely controlled by the included audio amplifier, and the overall figure is held to less than 0.25 percent for 100-percent modulation at 50 cycles. At high frequencies where the peak phase shift is less the distortion falls until it is entirely accounted for in the audio circuits. At the upper end of the audio spectrum, distortion owing to tuned circuits in the frequency multipliers rises slightly, but by reasonable design is held below 0.25 percent, measured without de-emphasis. It is much easier to contrive that the distortion be this low than it is accurately to measure it once secured!

The f-m noise originating in the modulator and in the band from 50 to 15,000 cycles, measured with 75-microsecond de-emphasis is somewhat better than 80 db below 100-percent modulation. This noise is made up of approximately equal contributions from the crystal oscillator plate circuit and the plate circuit of V_{4A}. It can be reduced still farther by designing for greater pulse bandwidth and higher tube currents, and by the special artifices described below. Microphonism is no practical problem at all with non-selected ordinary tubes. Because of the simplicity of the circuits involved shielding and isolation by ordinary means serves to suppress the noise effects of r-f feedback from high-level sections of the transmitter.

Increasing Phase Shift

There are two ways by which the total phase shift can be increased over the practical maximum of ±150 degrees. One of these is by cascading, or iterated modulation. The pulses at the plate of V_{4B} are similar in form and amplitude to those at the plate of V_{2A}. If, instead of coupling here to the grid of a multiplier, these pulses are fed to a duplicate of the circuit extending from V_{2B} to V_{4B} inclusive, another complete modulation process will have been encompassed. One stage of such cascading doubles the peak phase shift with the same percentage of f-m distortion and yet raises the f-m noise by less than 3 db. Thus the effective signal to noise ratio is improved by at least 3 db. The price paid for this iteration is two and a half additional tubes and a doubling of the audio power required to modulate. The process can be extended beyond two modulations. The other method involves generating two or more interlaced sawtooths at submultiples of the crystal frequency by means of a step-counter frequency divider; separately modulating pulses from each of the proportionately longer submultiple sawtooths; and recombining the sets of modulated pulses. The submultiple frequency, of course, must be more than twice as high as the highest modulating frequency involved.

In general, by the use of cascading and interlacing, as noted, by the use of a modification of the scheme employed in the Armstrong dual channel phase shift modulator, and by several other arrangements too detailed to describe here, the application of this system can be extended to cover a very wide field.

Commercial versions of the new modulator have been in use for the past six months at W2XMN-W2XEA, Alpine, New Jersey, and in the studio-transmitter link used to program KSBR, Mount Diablo, California.