LB-1086

FREQUENCY-MODULATION SYSTEM BASED ON SYNTHESIZED WAVE AND PHASE-SHIFT DETECTION

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Approved

Stuart Wm Seeley.

Frequency-Modulation System Based On Synthesized Wave And Phase-Shift Detection

An FM signal generator is described in which the sine-wave output is synthesised from a sawtooth oscillator. Extremely rapid frequency changes become possible so that the modulating frequencies may exceed the carrier frequency. A new detector system to use this "fast shifting" wave is also described.

Introduction

There are a number of uses of frequency modulation or frequency shift keying where the frequency swing or shift is comparable to the maximum information or keying frequency of the modulating signals. These uses include facsimile, 5 or 7 unit code, and similar communication systems. Apparatus limitations have generally restricted the generation of such signals at the transmitter to some form of reactance-tube modulation of an LC oscillator at some high frequency where the necessary swing may be obtained. This is then heterodyned with a fixed frequency oscillator and the beat frequency detected and filtered to place the FM wave in the desired band. The overall modulating system is therefore rather complicated, and is also usually troubled by warm-up drifts and associated difficulties in maintaining proper adjustment.

The frequency-modulated generator described in this bulletin allows a frequency swing of 5 or 10 to 1 or even higher if desired, and the wave is generated at the fundamental frequency without heterodyning. Since no LC tank circuits are involved, the frequency changes caused by a step function modulating signal are practically instantaneous. In addition a special method of wave shaping is used that forms the output signal into a sine wave with less than 2 percent harmonic distortion at all frequencies. Thus, the need for filters is avoided and the output wave remains in phase and without the time delay errors that filters usually introduce. Avoiding of filters also removes the filter-slope limitations on the rate of change of frequency of the generator.

With an FM generator having such rapid response to changes in frequency it is believed that uses will be found where the modulating frequency actually equals or even exceeds the carrier frequency. Such an FM wave would still carry all the modulating signal information but much of this information cannot be extracted by FM detector systems now in use. A new system of phase-shift detection has been developed for this use. The information recovery is at least twice that of the slope-filters or discriminators now in use, and can be still further improved where necessary.

The FM Generator

Two basic requirements must be met in the variable frequency oscillator to arrive at the final FM wave desired. These are (1) that the frequency-determining component of the oscillator must have no stored energy, so it can be readily shifted without causing transients, and (2) the output wave of this oscillator must always be constant in amplitude and of a form that lends itself to harmonic removal by amplitude correction rather than filtering.

In meeting the first requirement some form of RC or RL oscillator is indicated in which only the resistive element is the variable component for change of frequency. The second requirement becomes necessary where the frequency shift is greater than 2 to 1. If less than 2-to-1 shift is used it would be possible to build a low-pass filter to eliminate the second harmonic of the lowest frequency, while still passing the fundamental of the highest frequency encountered. Beyond these limits filtering within the usual meaning is impossible.

A diagram of the oscillator used in the tests made of this FM system is shown in Fig. 1. The oscillator is a sawtooth generator in which C_o is charged by current i_c furnished by the pentode T_2. When the charge across C_o reaches the value e_1 the gas triode T_1 is tripped on to discharge C_o. It immediately starts charging again towards formation of the next cycle, etc. The charging current i_c, the plate current of the pentode, is determined by the input signal to the grid of T_2, and is

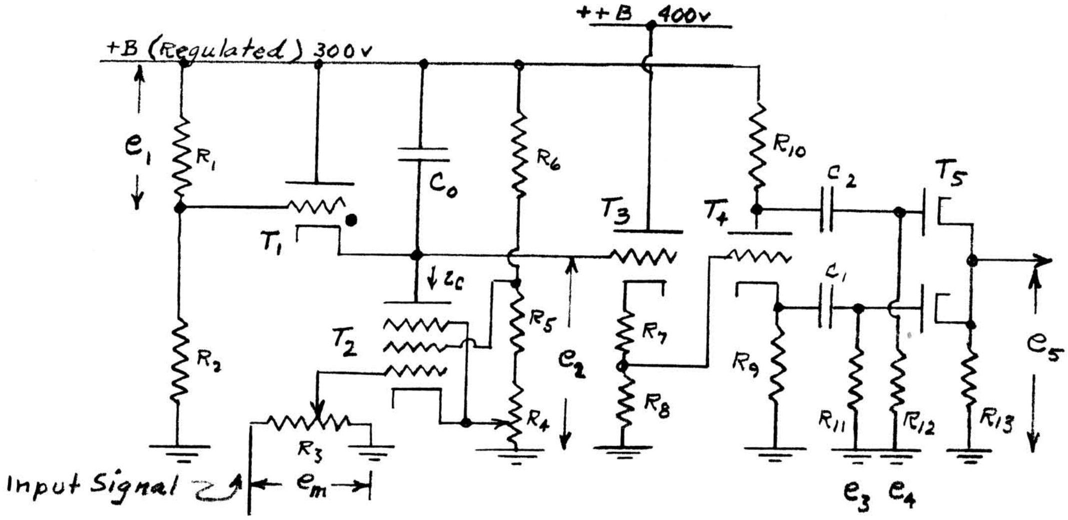
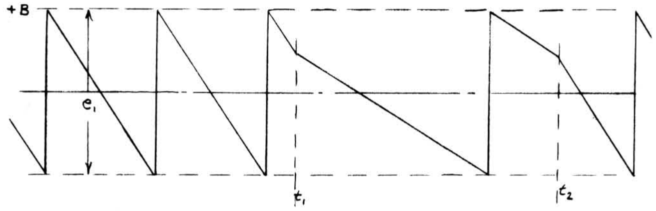


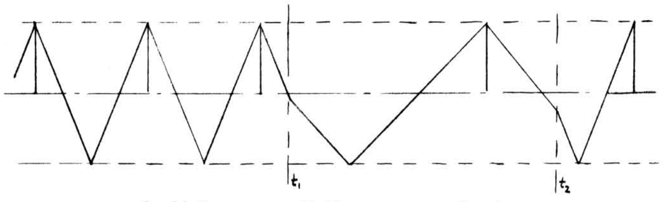
Fig. 1 - Basic FM oscillator and rectifier.

not affected by changing the plate supply voltage of T_2 over the limits of e_B to (e_B -e_1). Thus, the frequency of oscillation is increased as the grid signal of T_2 increases in a plus direction. The rate at which i_c may be changed is determined by the high frequency response of the tube T_2 as a current generator only, and the large capacitor C_o does not affect this rate. Response to sudden changes in e_m is therefore practically instantaneous compared to the frequency of the output wave.

The amplitude peak-to-peak value of the sawtooth voltage is constant at the value e_1 regardless of the number of times or amount the slope is changed during a cycle. A d-c centerline of e_2 is automatically obtained as a zero reference for the cathode followers T_3 and T_4 which follow the oscillator. T_4 supplies the two voltages e_3 and e_4 at 180 degree phase for rectification by T_5.



a. Oscillator wave e_2. Frequency shifted t_1 to t_2.



b. Voltage e_5. Full wave rectified e_2.

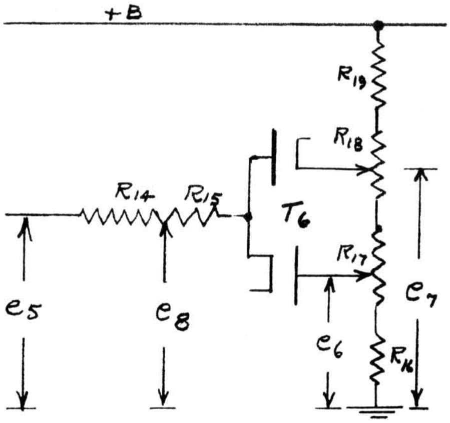
Fig. 2 - Wave analysis of oscillator in Fig. 1.

Fig. 2a shows the output of the oscillator in which the modulating voltage e_m was reduced for the time interval t_1 to t_2, giving a smaller charge current i_c and consequent reduction in frequency. The break in frequency or charging slope is just as sharp as the signal producing it. When this voltage is full-wave rectified the resulting output e_5 is shown in Fig. 2b. A sharp line extending to the center line from the plus peaks is shown. This is the extremely short time while T_1 is discharging C_o, and practically disappears before T_5 is reached if the follower tubes T_3 and T_4 are limited in high-frequency response by their circuit constants.

Shaping Circuits

It can be observed from Fig. 2b that at any steady-state frequency of operation, the output wave is a symmetrical triangular wave of constant peak-to-peak amplitude, and also of a constant harmonic content. No even harmonics are present because of symmetry, and the odd harmonics are present in values of $1/n^2$. Thus, the third harmonic has a value of 1/9, the fifth has 1/25, etc.

Two methods of reshaping this triangular wave have been used, both depending on using diode loads or limiters to alter the slope at definite fixed amplitudes. In the first of these methods two diode clippers were used to cut off the top and bottom peaks and form a trapezoidal wave. The clipper is shown in Fig. 3, and its action in Fig. 4. When the voltages biasing the limiter, e_6 and e_7, are set symmetrically above and



Slope change at $e_5 < e_6$ or $e_5 > e_7$. New slope set by ratio $R_{15}/R_{14} + R_{15}$.

Slope zero with $R_{15} = 0$, for trapezoidal output at e_8.

Fig. 3 - Shaper circuit.

below the d-c center line of the input wave e_5, and when $e_7 - e_6 = 0.667\ e_5$ (peak to peak), then the wave on the right in Fig. 4 is obtained. This is a special shape where the third harmonic is cancelled and the fifth harmonic is the first component above the fundamental frequency to appear. However, its percentage of fundamental frequency is lower than that produced by the two shapers finally used.

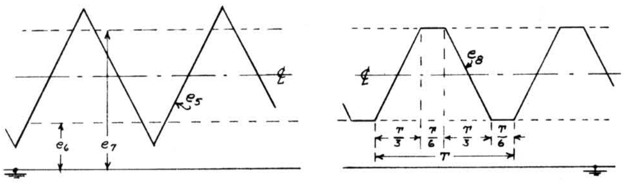


Fig. 4 - Shaper with $R_{15} = 0$ for trapezoidal wave. With these proportions third harmonic is cancelled.

When R_{15} is not zero in Fig. 3, the slope of the wave is reduced for all voltages less than e_6 or greater than e_7. Fig. 5 shows how the wave is reshaped if the slope is reduced to 0.5 its initial value.

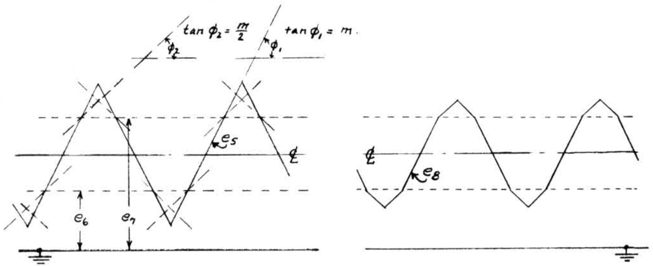
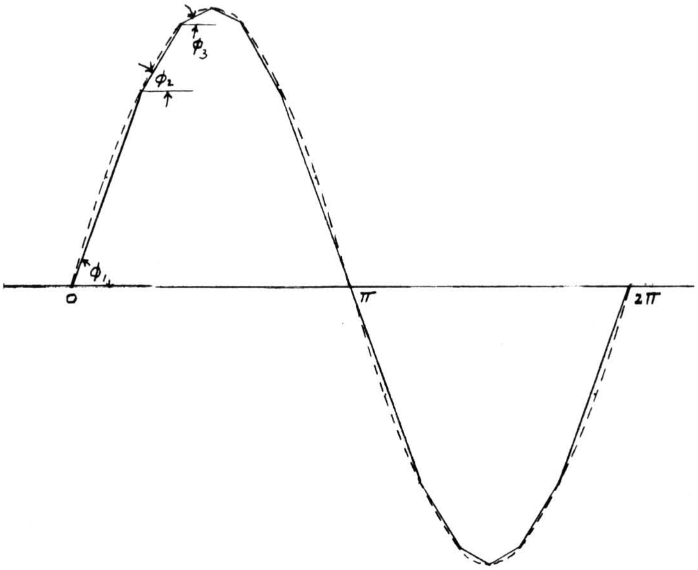


Fig. 5 - Shaper with $R_{15} = R_{14}$ and e_6 and e_7 set to change slope at each 45° of e_5.



—— synthesized sine wave.
- - - true sine wave.
Slope changes at 45° and 67.5°.
$\tan\phi_2 = 0.615 \tan\phi_1$.
$\tan\phi_3 = 0.351 \tan\phi_2$.

For first shaper
With $\tan\phi_2 = 0.615 \tan\phi_1$, $R_{15} = 1.60\ R_{14}$.
$e_7 - e_6 = 0.500\ e_5$ (peak-to-peak value).

For second shaper
With $\tan\phi_3 = 0.351 \tan\phi_2$, $R_{15} = 0.541\ R_{14}$.
$e_7 - e_6 = 0.646\ e_5$ (peak-to-peak values).

Fundamental frequency component approximately 98%.

Fig. 6 - Output after two shapers as in Fig. 3.

When two such shapers are connected in series, the effect in Fig. 6 may be obtained. By this proportioning of slopes, the near sine wave shown is synthesized. The wave is first "bent" at the 45 degree points by setting the first shaper to have its threshold voltages at 0.5 the peak-to-peak value of the input wave e_5. The values of R_{14} and R_{15} are proportioned to change the slope to 0.615 of its former value. This new portion of the wave will cross the true sine wave at 67.5 degrees, at which the second shaper threshold is exceeded. The second loading again changes the slope to where it will reach the true value at 90 degrees. In this manner, each half cycle of the wave is formed out of six straight lines and is correct in value at the 0°, 45°, 67.5°, 90°, 112.5°, 135° and 180° points. As this is a geometrical construction and controlled by amplitude only, the frequency of the wave has no effect, and the harmonic content is the same for all frequencies. In this case the fundamental accounts for approximately 98 percent of the output, with the sum of all harmonics approximately 2 percent.

Phase-Shift Detection

In normal FM detection two pieces of information or bits are obtained per cycle, one for each half cycle of the carrier. When an FM wave is passed through a discriminator or slope filter so that it may be amplitude detected these two "bits" appear as varying amplitudes of the half-cycle components. If the signal has been amplitude limited to obtain a square wave, the two cross-overs at zero voltage will provide the two pieces of information as a varying width of time per half cycle. In either case, or a combination of the two, the carrier must always be considerably greater than the modulating frequency for there to be enough bits of information to reconstruct the signal on detection.

When an FM subcarrier is used to transmit facsimile signals the black-and-white limit frequencies of the swing are usually separated by an amount approximately equal to the maximum keying frequency. Thus, in one particular facsimile equipment that is widely used for weather maps, etc., the maximum video or keying frequency is 625 cycles per second, and the FM limit frequency for white and black are 1600 and 2200 cycles. Note that the lowest frequency of 1600 cycles is approximately 2.5 times the highest modulating frequency, so at least five bits of information are obtained out of the detector to define the highest frequency it is required to transmit. There are undoubtedly telephone lines where this signal could be sent with lower distortion if the carrier swing was 800 to 1400 cycles instead of 1600 to 2200, but the detection system would be able to deliver only 2½ bits of information per keying cycle, and poor copy detail would be the result.

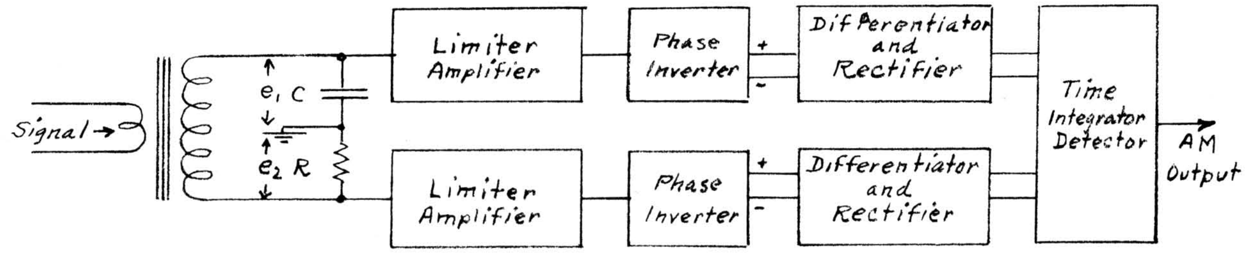
The phase-detection system described here would take this particular case cited above and deliver five bits of signal information per cycle while operating within the 800-to-1400-cycle swing. In principle the detector extracts the timing information of the zero voltage crossovers as in the usual FM detector but in addition adds a second set of timing information for the peaks at the 90 degree and 270 degree positions of each cycle. When these two groups are added, four separate time intervals are obtained per carrier cycle, each interval representing the four quandrants of the cycle. The information in the second group is not a repetition of the first, and actually represents new information. This is easily proved by modulating the FM generator to a different frequency for the time duration of each 1/4 cycle. When detected with the new system the variable time spacing for each carrier cycle quadrant is accurately shown.

Although all tests to date have been made using 90 degree separation of the "bits", there is no reason why some other angle could not be chosen. Thus, 60 degree intervals could be taken to give six "bits" of information per cycle. The net effect in any case is equivalent to conventional FM using a carrier frequency high enough to give the same total number of information bits at the rate of two "bits" per cycle. This opens up the possibilities of having the modulating frequency approach or even exceed the lowest frequency of the carrier swing while still being able to recover a large percentage of the modulating information.

Ninety Degree Separation Networks

Three types of networks have been tested that provide two FM signals that differ from each other by a 90 degree phase at all frequencies within the band to be used. These are shown in Figs. 7, 8 and 9. In Fig. 7 the complete detection system is shown, while Figs. 8 and 9 show only the differences in the phase shifters. All operate with the same limiters, inverters, differentiators and integrating detector shown in Fig. 7.

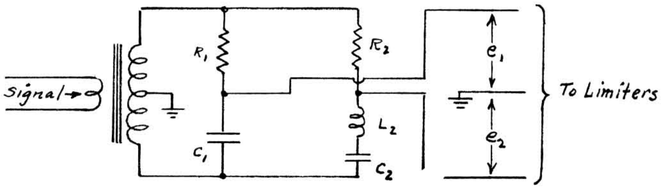
The chief requirement for the phase shifter is that the two output voltages derived from the common FM input be separated in phase by a constant angle at all frequencies in the FM band. A constant amplitude is not required as long as the changes in amplitude with frequency are not too great to be effectively removed by the limiter amplifiers following the shifters. The simplest such network is shown in Fig. 7 in which a resistance and capacitance are connected across the input signal. Since they pass the same current, the voltages e_1 and e_2



$R = X_C$ at midfrequency. e_1 and e_2 at 90°.

Fig. 7 - Recorder amplifier and detector system.

will be at 90 degree phase difference for all frequencies. If $R = X_C$ at the center frequency of the band, e_1 will lag by 45 degrees and e_2 lead by 45 degrees at this frequency. For higher and lower frequencies these angles will change but their difference will remain at 90 degrees. The amplitudes of e_1 and e_2 will be 0.707 at the center frequency, and amplitude changes with frequency are such that their vector sum is constant. Where the band spread is not over 2 or 3 or 1, the amplitude difference causes very little trouble. Other methods which have less change in amplitude are better for higher ratios of maximum to minimum carrier frequency.

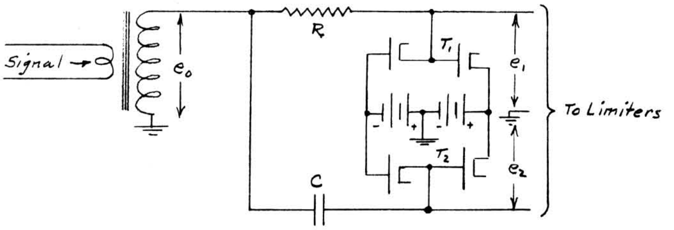


$X_{c_1} = R_1$ at midfrequency f

$X_{c_2} = X_{L_2}$ at midfrequency f_c $R_2 = 4.56\, X_{L_2}$ at f_c.

Fig. 8 - Networks for 90° separation of e_1 and e_2 to replace R and C in Fig. 7.

In the phase shifter shown in Fig. 8, two networks of a type discussed in U.S. Patent 2,641,645 are used. The first network consisting of R_1 and C_1 has a phase lag of 90 degrees at the center frequency of the FM band, and the second consisting of the series-tuned L_2 C_2 circuit and R_2 is tuned to have 180 degree lag at the center frequency. The resistor R_2 is then adjusted to the value shown and the phase difference between e_1 and e_2 is within ± 2 degrees of the 90 degrees desired over the range of 0.4 f_c to 2.5 f_c or a 6.25-to-1 frequency change. The advantage of this network over that in Fig. 7 is that the amplitudes of e_1 and e_2 are constant at all frequencies. Even though the accuracy of phase difference is less, it is sufficiently accurate for most purposes.



e_1 in phase with e_0. e_2 at +90° with e_0.

Fig. 9 - Current-fed limiters to obtain e_1 and e_2 at 90°.

A third method of obtaining the 90 degree phase difference is shown in Fig. 9. Two diode limiters or clippers are used, one being fed through the resistance R in the normal fashion so that the output e_1 is a square wave in phase with the input signal voltage. The second limiter is fed through the capacitor C and also delivers a square wave at e_2, but e_2 has its transition points at the peaks of the incoming signal rather than at the crossovers at zero voltage. It is therefore at a 90 degree lead over e_1. This phase lead is maintained for all frequencies in which the forward impedance of the diodes is small compared to X_C. Because the bias voltages on the diodes must be very small compared to the signal voltage this form of phase shifter-limiter should be preceeded by a high-gain voltage amplifier. However, the class A range of this amplifier cannot be exceeded or the voltage e_2 will not have its transitions at the true peak values of the wave. Therefore, the input level cannot vary over as wide a range as for the shifter in Fig. 8 without causing phase errors.

Other phase shifters for this type of service are known but have not been tested at this time. All tests of the system as a whole were made using the shifter in Fig. 8.

Complete Detector System

Fig. 7 shows in block diagram form how the complete detector system operates. The two voltages e_1 and e_2 derived from the phase shifter are each amplified and limited to form a high-voltage square wave with accurately spaced transition points. A phase inverter follows each limiter so that both plus and minus forms of the square are available. These two inverter outputs are then differentiated and full-wave rectified so that a plus pulse is obtained for each transition point. When the pulses from the second phase-shifted signal are added four pulses per carrier cycle are obtained, and the time spacing between each two pulses represents the duration time for that 1/4 cycle of the carrier frequency.

Where wide frequency swings are contemplated an integrating type of detector may be used on these pulses to obtain an amplitude varying inversely with frequency. A capacitor is connected from ground to +B through a series resistor so that over short periods of time the voltage increase is linear. Each pulse from the detector discharges the capacitor so that it starts recharging from zero again. The peak voltage attained during each 1/4 cycle then represents the time interval between pulses. Reducing the resistor value so that the charging rate is nonlinear but comes well up on the exponential curve will make the average amplitude changes more nearly linear with changes in frequency. Both types of detector output are shown in Fig. 11 where a wave analysis of the complete system is given.

The Complete System And Performance.

The block diagram in Fig. 10 shows how all of the component parts described are combined to form a complete FM signaling system. Since circuits for all the major items have been given, a complete circuit is unnecessary here. Tests on such a system have been made in which carrier limits of 500 cycles to 2000 cycles were used. Various modulating signals have been put over the circuit to see how complete the detection is, and the results have fully met expectations. A step-function generator was built that could be used to represent any type of facsimile signal one might encounter from a ten-step "light wedge" to an isolated full-amplitude "black" pulse on a white background. The recovery of all of these signals was complete even when any one pulse or step was represented by a frequency change of only 1/4 cycle duration.

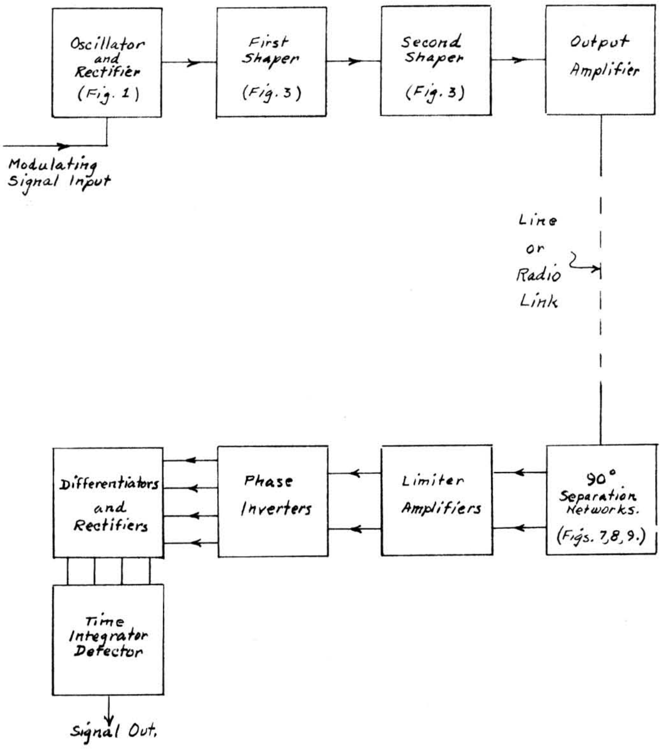


Fig. 10 - Complete FM system using generator in Fig. 1 with synthesized sine wave output and phase detection.

Fig. 11 shows a wave analysis of the complete system under varying input signals as in (A). The frequency of the carrier for the various signals is shown at the left. The time intervals marked ΔT represent 0.5 millisecond spaces, so the on-off keying on the right end of (A) is square-wave keying of 1000 cycles fundamental frequency.

The oscillator-rectifier wave generated is shown in (B), and (C) shows the wave after shaping it to near sine waves. It should be noted here that the shaping is accurate enough for the 90 degree detector networks to operate almost exactly as calculated for sine waves, so the two recorder signals shown in (D) and (E) are spaced in phase according to the crossovers and peaks of the wave (C).

The sum of all pulses from (D) and (E), as shown in (F) is used to actuate a charge-discharge capacitor integrator which delivers an output as in (G). If linear charging of the capacitor is used, the output is as shown in dotted lines. When the exponential charging is used, set here for a time constant of 1/4 of Δt or 0.125 millisecond, the solid shaded output in (G) is obtained. With this particular time constant the amplitude difference is reduced, but becomes more linear over these frequency limits.

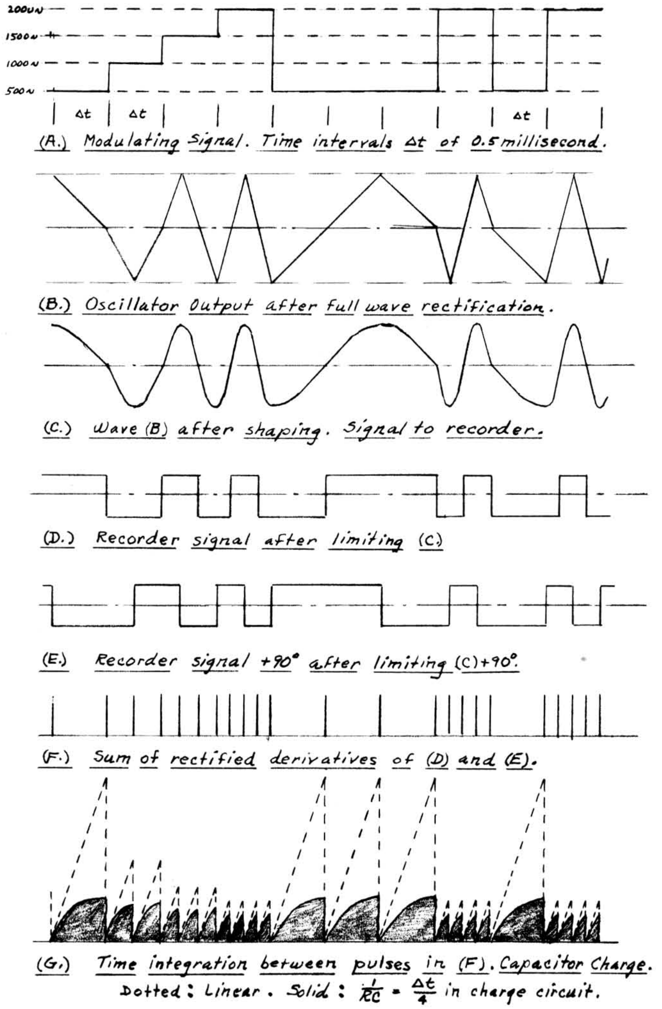
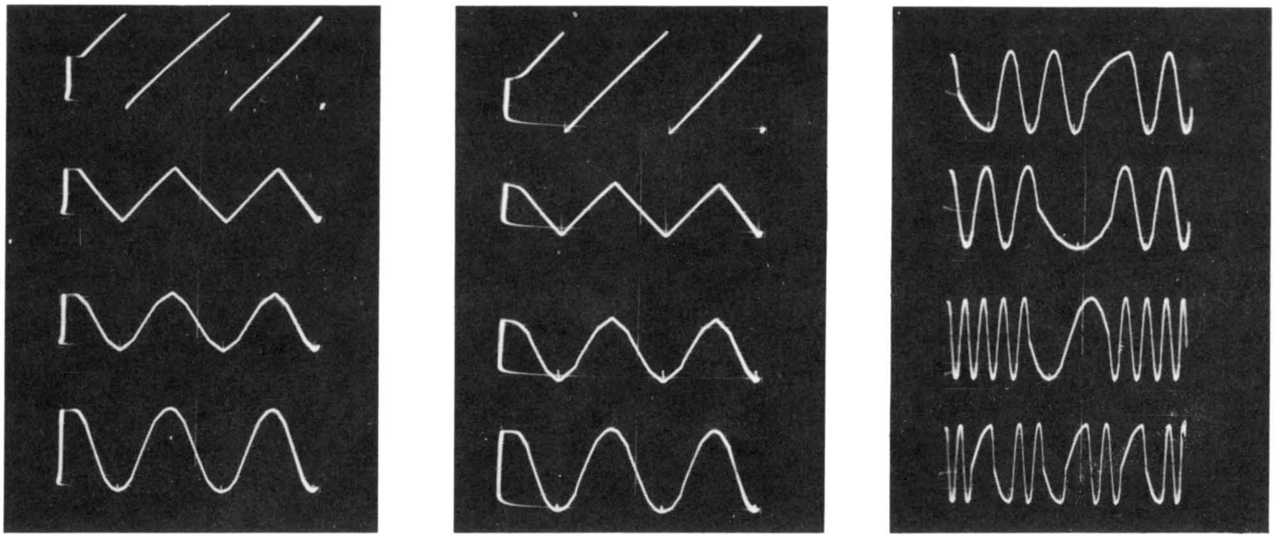


Fig. 11 - Wave analysis of complete system in Fig. 10.

Actual oscilloscope observations have been made of the analysis in Fig. 11, along with other groupings of test signals and these tests all lead to the conclusion that both the generator and detector perform their functions very well, and that the resulting signal is the equal of



(A) Synthesis of sine wave
1. Sawtooth at 500~.
2. Full-wave rectified sawtooth
3. Output of first shaper.
4. Output of second shaper.

(B) Synthesis of sine wave
1. Sawtooth at 2000~.
2. Full-wave rectified sawtooth
3. Output of first shaper.
4. Output of second shaper.

(C) On-off keying of FM generator
1. 1/4 ~of 500 ~+ 9/4 ~of 2000 ~.
2. 1/2 ~of 500 ~+ 9/2 ~of 2000 ~.
3. 1 ~of 500 ~+ 9 ~of 2000 ~.
4. { 1/4 ~of 500 ~+ 1/4 ~of 2000 ~.
+ 1/4 ~of 500 ~+ 7/4 ~of 2000 ~.

Fig. 12 - Oscilloscope records of FM generator performance.

that derived from a conventional FM generator at twice the carrier frequency using a conventional detector.

Fig. 12 is a photograph of the FM generator performance. Steady-state conditions are shown in A and B, and the effects of high-speed square-wave keying is shown in C. Figs. 12a and 12b show that the filtering action of the synthesizing system is the same at 500 or 2000 cycles, and that no phase change occurs in the shaping process. All four waves for each frequency were obtained with the same horizontal sweep of the oscilloscope locked in phase by the sawtooth generator.

Fig. 12c shows four conditions of keying, where either 1/4, 1/2 or a full cycle of the lower 500-cycle frequency is keyed into the oscillator while it is normally running at 2000 cycles. In the fourth wave two keying pulses are used to give two 1/4 cycle intervals of the 500-cycle frequency, and these are separated in time for a 1/4 cycle interval of the 2000-cycle frequency. The sharpness of the keying, and effectiveness of the synthesizing filter under transient conditions is illustrated in these photos.

High-Frequency Operation

When used at higher frequencies than those involved in these tests, the gas triode discharge of the generator capacitor will have to be replaced by a hard-tube trip circuit to obtain the necessary speed of response. Other than this change, operation of the remainder of the circuit should be possible at least to 100 kc and probably to 1 Mc without any additional work other than rescaling the circuits for the higher frequency response. Adaptation of the detector circuits to the higher frequencies involves only changing the phase-shift component values if the band spread of 6.25 to 1 of the present networks is not exceeded. For higher shift ratios new networks will have to be calculated.

Conclusions

An FM signal generator has been built in which the frequency response to changes in the modulating signal is practically instantaneous. The carrier is generated at the fundamental frequency and may readily be shifted in frequency by ratios as high as 5 or 10 to 1. Geometrical shaping or synthesizing is used to derive a near sine wave output at all frequencies, and the filtering out of harmonics is therefore unnecessary.

A new form of phase shift detection has been built for use with this "fast shift" FM wave that delivers usable signals of full amplitude when the carrier has shifts in frequency of only 1/4 carrier cycle time duration. Information recovery of this detector was set for four bits of modulating signal information per carrier cycle for all tests made, but the same principles can be used to obtain six or even more bits per cycle if required.

A series of tests and demonstrations have been made in which the carrier was keyed between the frequencies of 500 to 2000 cycles, a 4-to-1 ratio, and with keying rates as high as 1000 cycles square wave. Information recovery in the detector was excellent, even though the 1000-cycle keying rate is twice the frequency of the lowest carrier swing.

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