LB-865

TRANSISTOR OSCILLATORS

RADIO CORPORATION OF AMERICA

RCA LABORATORIES DIVISION

INDUSTRY SERVICE LABORATORY

RADIO CORPORATION OF AMERICA

RCA LABORATORIES DIVISION

INDUSTRY SERVICE LABORATORY

LB-865

Transistor Oscillators

Approved

Stuart Wm Seeley

Transistor Oscillators

Introduction

In this bulletin the basic oscillators which utilize current multiplication transistors are described and their mode of operation is discussed. A fundamental mathematical criterion for oscillation in these circuits is given and the physical significance of current feedback is explained as it applies to their operation.

The generation of sinusoidal voltages by tuned-circuit, crystal-controlled and phase-shift type oscillators is discussed. In connection with these circuits means are described for improving their high-frequency operation and for obtaining frequency multiplication.

Basic relaxation oscillators are presented. These oscillators may be arranged to be free running or triggered. Their operation is explained by means of the voltage and current waveforms developed at the transistor electrodes.

By combining the features of the sine-wave oscillator with those of the relaxation oscillator, self-quenching oscillation, super-regenerative detection or stabilized frequency division may be obtained. Finally, the practical selection of the circuit parameters is discussed.

General Discussion

This bulletin discusses the phenomenon of oscillation which may be associated with a number of crystalline devices and in particular the transistor. While the transistor is presently the foremost among these devices, the utilization of solid state elements as oscillators is not new.

For a considerable time oscillators using crystal rectifiers have been known.[1] These circuits make use of the negative resistance which some crystal rectifiers exhibit under certain operating conditions and particularly near breakdown. A current multiplication transistor also exhibits negative resistance under certain conditions and this phenomenon is primarily a function of its current gain, α. Most point-contact type transistors (having rectifying electrodes) as well as certain other types of transistors exhibit short-circuit collector current increments (Δi_c) which are larger than the corresponding emitter current increments (Δi_e):

$$\left.\frac{\Delta i_c}{\Delta i_e}\right|_{E_c} \equiv \alpha > 1$$

The oscillators to be described are based on the negative resistance characteristics of those transistors having current multiplication. Since a vacuum-tube amplifier (except those operated so as to have secondary-electron multiplication) does not have a current exceeding unity, this unique characteristic of a transistor permits the design of many unusual circuits.

Transistor oscillators[2] having an external feedback path providing voltage feedback were described in the literature shortly after the transistor[3] was first disclosed. However, it is not with respect to this type of operation that the transistor exhibits its most unique and useful mode of operation. Rather, due to the negative resistance exhibited by the current multiplication transistor, various oscillators can be designed which do not require voltage feedback.

LC Sine-Wave Oscillators

Fig. 1 shows a conventional equivalent network[4] of a transistor (indicated by the dotted rectangle) and the associated external circuit elements which are indicated as impedances. From this equivalent circuit equations can be derived which indicate that such a circuit will oscillate when the following condition is met:

$$\frac{Z_e + r_e}{Z_b + r_b} \leq \frac{r_m - Z_e - r_e}{Z_c + r_c} - 1 \qquad (1)$$

where

$$\frac{r_m - Z_e - r_e}{Z_c + r_c} \equiv \alpha$$

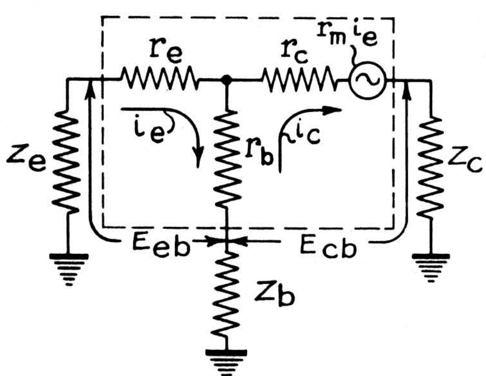

Fig. 1 - Equivalent circuit diagram of a transistor.

The symbols used in Eq. (1) are all indicated in Fig. 1. It will be assumed that r_e, r_b, r_c and r_m are constant over the operating range to be considered. Accordingly, only the values of the external impedances Z_e, Z_b and Z_c can be selected at will. As a necessary condition for oscillation, α must be greater than unity. Under this condition, oscillations may be produced by increasing the value of Z_b (case A), by decreasing the value of Z_e (case B) or by decreasing the value of Z_c (case C). By any of these three conditions Eq. (1) may be satisfied. Sine-wave oscillators[5] of the LC type corresponding to cases A, B and C are illustrated in connection with Figs. 2, and 4 to 8.

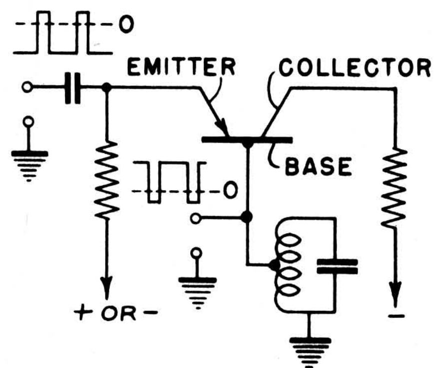

Fig. 2 - Sine wave oscillator (case A).

A tuned-circuit oscillator corresponding to case A is shown in Fig. 2[6]. A grounded parallel-resonant circuit is connected to the base. In order to enable an impedance adjustment of a portion of the total impedance of the resonant circuit presented to the base, the base is connected to an intermediate point of the inductor. With this arrangement, the base impedance Z_b becomes a maximum at the resonant frequency of the tuned circuit. The collector is biased in the reverse direction and the emitter in the forward direction, both with respect to the base as indicated. Both the emitter and the collector may be connected directly to their voltage supplies, but in view of the limited current-carrying capabilities of the transistor, current-limiting resistors may be necessary.

Fig. 3 illustrates the resistance which appears looking into the base, R'_b, as a function of the voltage between emitter and base, E_{eb}, in a regenerative amplifier. Between the ordinate axis (E_{eb} = 0) and the dotted line m (E_{eb} = m) the internal base resistance R'_b is negative, and within this range of emitter voltage values oscillation may take place; to

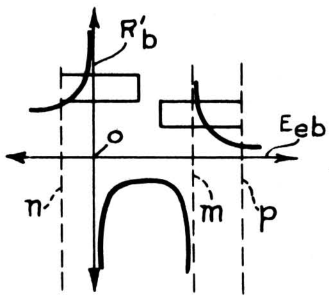

Fig. 3 – Base resistance as a function of the emitter-to-base voltage.

The left of the y-axis and to the right of the line *m* no oscillation is possible. Consequently, the emitter of the circuit of Fig. 2 could be biased to a value to the left of the y-axis as shown by dotted line *n* to prevent the circuit from oscillating. Now, by applying a positive pulse to the emitter the circuit will oscillate for the duration of the trigger pulse provided the pulse amplitude is sufficient to carry the voltage E_{eb} to the right of the y-axis as shown in Fig. 3. The same result may be obtained by applying a negative trigger pulse to the base as indicated in Fig. 2. The circuit of Fig. 2 may also be triggered into oscillation by the application of a negative trigger pulse to the collector. This has the same effect as a negative pulse applied to the base, for the collector current increases in response to the negative collector pulse, resulting in a larger current through the base impedance which, in turn, drives the base voltage more negative.

The curves of Fig. 3 also show that for higher positive values of E_{eb} the internal base resistance R'_b again becomes positive. Hence, by biasing the emitter to a value as shown by the dotted line *p*, the circuit of Fig. 2 will also be normally quiescent and may be triggered by the application of a negative trigger pulse to the emitter or by a positive trigger pulse applied to the base or collector of sufficient amplitude to carry E_{eb} to the left of line *m*.

At frequencies of the order of a few hundred kilocycles the transistor constants are no longer pure resistances, but exhibit reactive components of appreciable magnitude. Therefore, at these higher frequencies a phase shift is developed between the emitter and collector currents. When this phase shift becomes too large, the real component of the collector current, which is returned to the emitter, may no longer be of sufficient magnitude to sustain oscillation. In order to secure oscillatory operation at these higher frequencies, it will be found necessary to compensate for this phase shift. Perhaps one of the simplest approaches to accomplish this end is that shown in Fig. 4 wherein shunt capacitances of a few micromicrofarads each are applied to both the emitter and collector electrodes. Either one of these shunt capacitors will provide a degree of compensation. In this particular oscillator the maximum oscillation frequency may be increased by a factor of two over that which may be obtained without phase shift compensation. This manner of compensation is generally applicable to current feedback oscillators.

Regeneration in the circuit of Fig. 4 is enhanced by the addition of voltage feedback through the emitter resistor which is tapped onto the oscillatory tank circuit. The size of the resistor connecting the emitter electrode to the base tank has a large influence on the upper limit of the oscillatory frequency. As the resistance is increased, the upper frequency of oscillation increases, but beyond an optimum resistance value the upper frequency limit decreases.

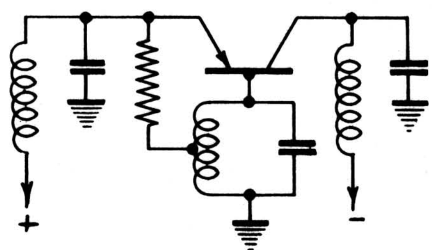

Fig. 4 – Sine wave oscillator suitable for high frequency operation.

Oscillators of the type shown in Fig. 2 may readily be modified to provide frequency multiplication. A parallel resonant circuit connected to the collector may be tuned to a harmonic of the frequency to which the parallel resonant base circuit is tuned. This arrangement is practical since the collector circuit impedance remains at a relatively low value at the fundamental frequency of oscillation. Such a circuit is shown in Fig. 5.

The flexibility of the transistor operating under conditions of current feedback is further illustrated by reference to Fig. 6. This circuit

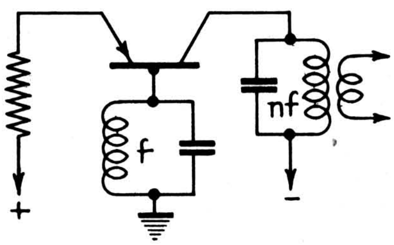

Fig. 5 – Sine wave oscillator arranged as frequency multiplier.

operates under the conditions of case B. Here the emitter impedance Z_e becomes a minimum at the resonant frequency of the series resonant circuit. In order to satisfy the condition of Eq. (1), a resistor is connected between base and ground. The emitter requires a negative bias voltage in this case to maintain its potential slightly positive with respect to the base; in view of the collector current flowing through the base impedance, a relatively high negative voltage is developed at the base.

Fig. 7 illustrates an oscillator which operates under the conditions of case C. Here the collector impedance Z_c is made a minimum at the resonant frequency of the series resonant collector circuit. The oscillator of Fig. 8[7] has a series resonant circuit connected directly between emitter and collector and combines the features of both cases B and C. A circuit combining the features of all three cases is also feasible.

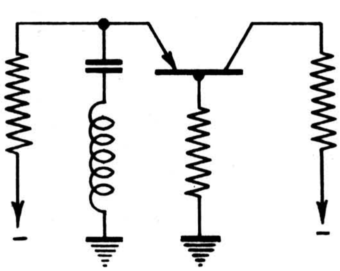

Fig. 6 – Sine wave oscillator (case B).

For the oscillators of Figs. 6, 7 and 8 the curves of Fig. 3 still represent the internal base resistance R_b'. These oscillators may again be biased to the left of the y-axis of Fig. 3 and triggered by the application of a positive pulse to the emitter or by the application of negative pulses to the base or collector. Such a triggered circuit is shown in Fig. 8. On the other hand, if the oscillator is biased to the right of line *m* of Fig. 3, it may be triggered into oscillation by applying negative pulses to the emitter or positive pulses to base or collector. The same result will be obtained by varying any of the external network resistances either mechanically or electronically to bring the circuit into or out of its oscillating range. Preferably the emitter resistance should be varied since it provides the greatest control.

Frequency stability with respect to variations in the supply voltage may be obtained by operating these circuits from a common bias source. This will be evident from an inspection

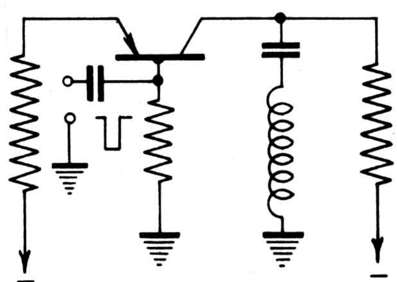

Fig. 7 – Sine wave oscillator (case C).

of Fig. 9, which indicates that frequency varies directly with emitter voltage E_{eb} and inversely with collector voltage E_{cb}. These curves centered at about 500 kc show a 13 per cent frequency change for a 10 per cent change of collector current or for a 14 per cent change of emitter current. Hence, operation from a common bias source is desirable. On the other hand, the phenomenon indicated in Fig. 9 may be used to advantage to obtain frequency modulation of these oscillators. This may be accomplished by varying either the bias voltages or the external resistances in such a manner as to cause variations in the effective emitter or collector voltages.

The operation of these three types of LC sine-wave oscillators may also be explained on the basis of the current multiplication of the transistor oscillator network. Reference is again made to Eq. (1) in which

$$\alpha \geq 1 + \frac{Z_e + r_e}{Z_b + r_b} \qquad (2)$$

As before, this equation represents a necessary condition for oscillation. Since Z_e, r_e, Z_b and r_b are all positive and finite, α must be greater than unity to satisfy Eq. (2) and to cause oscillation. In the oscillator of Fig. 2 the collector current i_c is fed back to the emitter at the resonant frequency of the base circuit; at other frequencies a portion of the collector current i_c is returned to the base

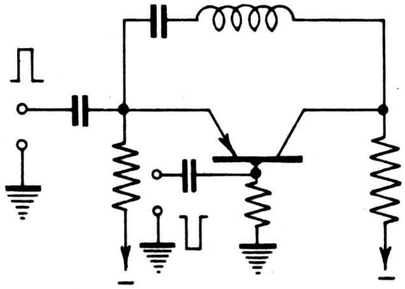

Fig. 8 – Sine wave oscillator (case B and C).

through the base impedance which now has a lower value, and hence oscillations cannot be maintained. As is shown in Fig. 1, i_e and i_c flow in opposite directions through Z_b and are out of phase. With a series resonant circuit connected to the emitter (Fig. 6) or to the collector (Fig. 7) a low impedance path is provided at the resonant frequency of the series resonant circuit between collector and emitter for feeding back a portion of the collector current i_c sufficient to sustain oscillation. The relatively large external resistance in the base circuit prevents a substantial portion of the collector current from returning to the base. In the oscillator of Fig. 8 there is, of course, a direct low-impedance path for i_c between collector and emitter.

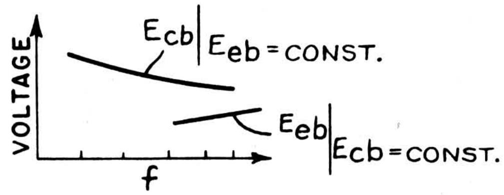

Fig. 9 – Operating frequency of sine wave oscillators as a function of the applied voltages.

Thus, it has been shown that the tuned-circuit transistor oscillator represents a very simple oscillator. It is certainly one of the most generally useful oscillators. The circuits described are unusually economical in component parts, while presenting a high degree of flexibility in circuit design.

The field of application for these tuned-circuit oscillators is generally not unlike that to which their vacuum-tube counterpart is applied. Of course, these transistor oscillators must be utilized in accordance with their frequency range and power limitations. However, it is frequently undesirable to use the oscillator as a power source.

The local oscillator of superheterodyne radio receivers presents an immediate application of the tuned-circuit oscillator. This circuit type also lends itself readily to the pulse modulation of various information-handling systems.

Crystal-Controlled Oscillators

The transistor oscillator is readily adapted to crystal frequency control. However, there are certain necessary operating conditions which must be recognized and taken into account. This oscillator type is especially valuable since the previously discussed oscillators tend to be frequency sensitive with respect to the applied voltages. The conventional vacuum-tube crystal-controlled oscillator includes a piezoelectric crystal which has a very high Q at its resonant frequency. In order effectively to couple such a crystal to a transistor, a high impedance must be provided looking into the electrode to which the crystal is connected to preserve the Q of the crystal. Fortunately, by suitable choice of the operating conditions of a current multiplication transistor, a high impedance may be provided looking into any of its three electrodes[8] to prevent loading of the crystal. Thus, the transistor provides a high degree of flexibility in the design of crystal-controlled oscillators.

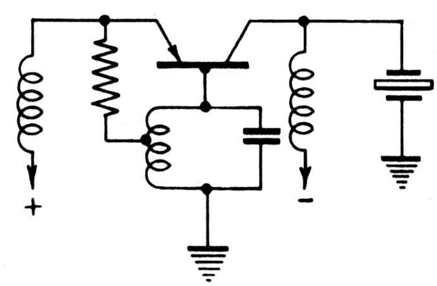

Fig. 10 – Crystal controlled oscillator; crystal connected to the collector.

The oscillators of Figs. 10, 12 and 14 combine the features of the LC sine-wave oscillators previously described with the high impedance of the electrode to which the crystal is connected. As illustrated in Fig. 10, the crystal may be connected between collector and ground. The resistance looking into the collector, R'_c, shown as a function of i_c in Fig. 11, indicates that R'_c approaches infinity when

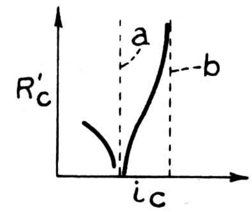

Fig. 11 - Collector resistance as a function of the collector current.

i_c approaches the dotted line *b*; in the neighborhood of the dotted line *a*, R'_c approaches zero. A parallel resonant circuit is coupled to the base and a feedback path which may include a resistor is provided between the emitter and the base resonant circuit.

The crystal may also be connected to the emitter as indicated in Figs. 12 and 14. The resistance looking into the emitter, R'_e, is shown in Fig. 13 as a function of i_c. Near the dotted line *c*, R'_e approaches infinity. Fig. 12 shows a parallel resonant circuit connected to

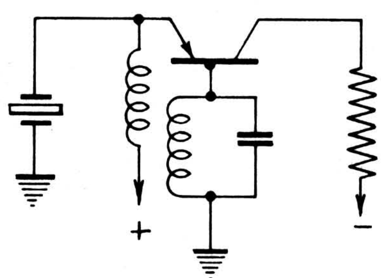

Fig. 12 - Crystal controlled oscillator; crystal connected to the emitter; parallel resonant circuit connected to the base.

the base, and in Fig. 14 a series resonant circuit is connected to the collector. In the oscillator of Fig. 14 a large resistor is connected to the base as a necessary condition for oscillation and to produce the high emitter impedance. In this oscillator the crystal and the series resonant circuit may also be exchanged. The feedback principle by which these

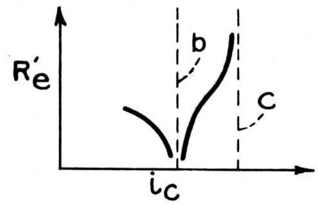

Fig. 13 - Emitter resistance as a function of the collector current.

crystal-controlled oscillators operate will be evident from the preceding explanation of the LC sine-wave oscillators.

In Fig. 15 the crystal is connected to the base and is bypassed for direct current by an r-f choke. In this oscillator circuit use is made of the parallel resonance of the crystal. A series resonant circuit is connected between collector and ground and tuned approximately to the crystal frequency. It is also possible to connect the series resonant circuit between

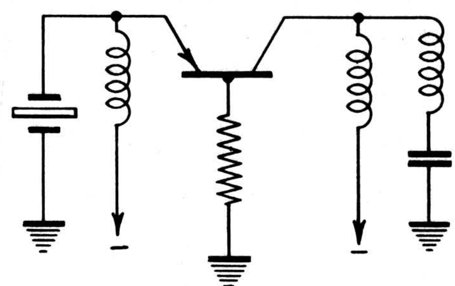

Fig. 14 - Crystal controlled oscillator; crystal connected to the emitter; series resonant circuit connected to the collector.

emitter and ground. Fig. 16 shows that the resistance R'_b, which appears looking into the base, approaches infinity as i_c approaches the dotted line *b*. In this manner R'_b can be made large enough to present only a small load to the crystal. Dotted lines *b* in Figs. 11, 13 and 16 correspond to the same value of i_c for a given transistor. In the crystal-controlled oscillators discussed here, it should be pointed out that the resonant circuit may be replaced by a resistor. However, this modification will increase the harmonic content of the output signal, while the presence of the tuned circuit will tend to enforce oscillation at the desired frequency. Hence, in those circuits where a fixed frequency oscillation is demanded, the crystal-controlled oscillator should find wide applications.

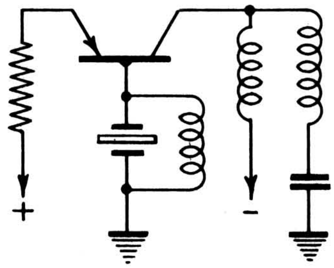

Fig. 15 - Crystal controlled oscillator; crystal connected to the base.

Phase-Shift Sine-Wave Oscillators

A satisfactory oscillator for use especially in the audio range where fixed frequency operation is called for is the phase-shift oscillator. This type of oscillator is desirable because it is able to generate a very pure sine wave and to maintain its frequency relatively independent of supply voltage variations.

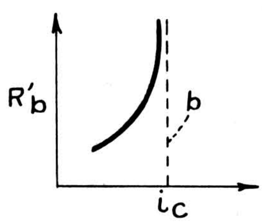

Fig. 16 - Base resistance as a function of the collector current.

A practical phase-shift oscillator is shown in Fig. 17. Feedback is furnished by a resistive-capacitive network, which may be considered a band-elimination filter. At the predetermined frequency the network exhibits a zero-degree phase shift and maximum attenuation.[9] Regeneration is provided by the base resistor and is only effective at the operating frequency. At other frequencies degeneration provided by the flow of collector current through the network into the base inhibits oscillation. Hence, for a current multiplication transistor, oscillation will take place at the frequency for which the network provides maximum attenuation.

It is also feasible to replace the zero phase-shift network by a 180-degree phase-shift network in the oscillator of Fig. 17. In that case, the circuit oscillates by virtue of voltage feedback between collector and base which is of the correct phase to promote oscillation.[10]

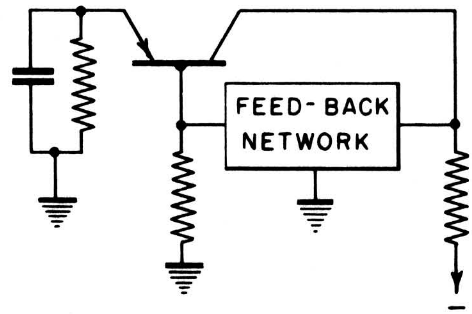

Fig. 17 - Phase shift or feedback network oscillator.

Relaxation Oscillators

One of the more important fields of application of the transistor is the relaxation oscillator. In this connection it finds its chief merit because even a moderate degree of power generation is usually unnecessary. The transistor exhibits some attractive characteristics when operated in this circuit type. At the present stage of development, most transistors are still limited in power-handling ability and the point-contact transistor has a high noise level; hence, the relaxation oscillator becomes especially important since normally neither of these limitations are of concern in this type of application.

A basic type of relaxation oscillator is that which employs a resistive-capacitive time-constant network and which has previously been described in the literature.[11] In this oscillator a capacitor is connected between collector and ground or between emitter and ground. This capacitor is charged at a relatively slow rate from the collector or emitter voltage supply through a resistor. Ultimately, when the voltage across the capacitor has attained a certain value, the transistor reaches its regenerative region. When this occurs, the capacitor is discharged at a relatively rapid rate through the transistor and during each oscillatory cycle a saw-tooth wave is developed.

A self-quenching oscillator also requiring a current-multiplication transistor is illustrated in Fig. 18. The capacitor connected between collector and ground is charged from the collector voltage supply through the collector resistor; a parallel resonant circuit is connected to the base. The time constant of the RC circuit connected to the collector should be larger than the period of the LC circuit connected to the base.

These two circuits may be so arranged as to operate as frequency dividers. To this end they are biased to free-running operation, but are synchronized in time by externally applied voltage pulses. While these circuits will operate satisfactorily in applications where division ratios of three or four to one are required, they are not stable enough presently for reliable operation at higher division ratios. This is due primarily to the free-running frequency dependence on the bias voltage.

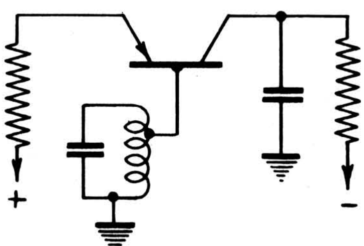

Fig. 18 - Self-quenching oscillator or stabilized frequency divider.

The operation of this circuit may be more easily understood by reference to Fig. 19 which shows the collector voltage wave e_c and the base voltage wave e_b. The collector circuit operates independently of the base circuit and produces the saw-tooth wave associated with the RC relaxation oscillator. The operation of the base circuit, however, is quite dependent upon the amplitude of the voltage excursion of the collector. It will be evident that without the collector capacitor, the circuit will act as a sine-wave oscillator as previously described. However, in the circuit of Fig. 18, as the collector capacitor charges in the negative direction, the transistor is carried into its regenerative region. At some point regeneration becomes sufficiently great to support oscillation in the base tank circuit once it has been initiated by a noise pulse or other voltage transient. The oscillation attains its peak

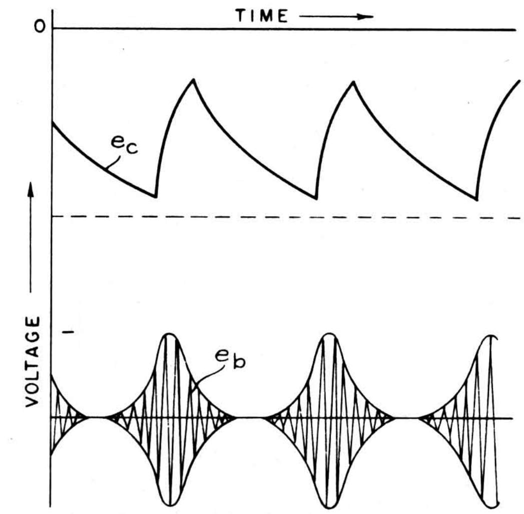

Fig. 19 - Voltage waves of the self-quenching oscillator of Fig. 18.

amplitude at the moment the collector capacitor starts to discharge. Thereafter, the oscillations are sustained by the energy stored in the tank circuit and their duration becomes solely a function of the Q of the circuit and the load imposed by the circuit constants. Under proper conditions, the sine-wave oscillations may be made to be continuous but with varying amplitude.

The oscillator of Fig. 18 may be modified as shown in Fig. 20 to operate as a super-regenerative detector suitable as a simple radio receiver. A feedback path which may include a resistor is provided between the emitter and the parallel resonant base circuit.

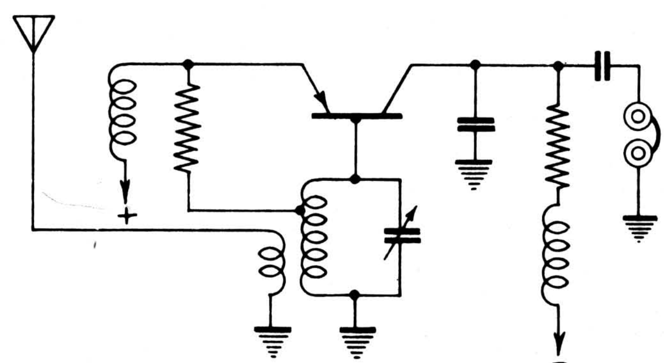

Fig. 20 - Super-regenerative detector.

An amplitude-modulated (AM) carrier wave may be impressed on the base circuit through an antenna and an inductor. The quench frequency is determined by the time constant of the collector circuit, while the frequency of the sine wave developed in the base circuit is determined by the constants of the tuned circuit. The selectivity of the detector is due to the fact that only if a carrier is impressed on the base tank whose frequency equals the resonant frequency, will a voltage be developed across the base circuit.

Fig. 21 illustrates the collector voltage wave of the circuit of Fig. 20 which is similar to that shown in Fig. 19 and the emitter voltage wave e_e. If an AM wave is impressed on the base circuit having a carrier frequency equal to that of the base tank circuit, the envelope of the emitter voltage wave e_e rises earlier than in the absence of an impressed AM wave. This

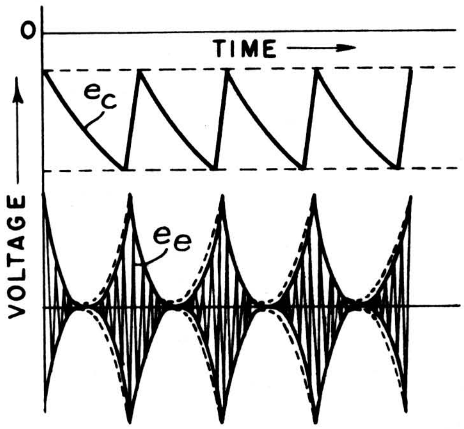

Fig. 21 - Collector and emitter voltage waves of the detector of Fig. 20.

represents an earlier initiation of the regenerative cycle. The new voltage envelope is shown by the dotted lines. Fig. 22 illustrates the effect of the impressed AM wave on the collector voltage e_c and on the average collector current i_c. Dotted line *q* indicates the collector voltage at which the charge cycle of the collector capacitor starts in the absence of the impressed AM wave. Dotted line *r* indicates the collector voltage where the discharge cycle of the capacitor normally is initiated. Due to the impressed carrier wave, the capacitor charge and discharge cycles are initiated earlier. Thus, modulation of the impressed AM wave is effectively reproduced as a modulation of the collector current.

The circuit should be designed to maintain a quency frequency above the audio range. The average collector current i_c represents the modulation signal which may be reproduced by earphones coupled to the collector, or which may be applied to a succeeding stage for greater amplification. As in the case of a vacuum tube super-regenerative detector, a hiss is heard in the absence of a carrier wave; this hiss disappears as soon as the detector is tuned to a received signal.

A self-quenching oscillator similar in operation to that of Fig. 18 is obtained when the capacitor is connected to the emitter and charged from the emitter voltage supply through a resistor.

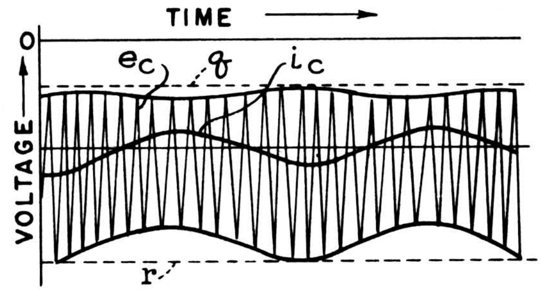

Fig. 22 - Wave shapes of the super-regenerative detector indicating the effect of an impressed AM wave.

The circuit of Fig. 18 may also be operated such that the time constant of the RC network connected to the collector is only slightly larger than the period of the LC base circuit. Thus, during each charge and discharge cycle of the collector capacitor there may be a few oscillations or possibly only one cycle of the sine wave developed across the parallel resonant base circuit. The voltages e_b, e_c and e_e developed by such an RC-LC relaxation oscillator are illustrated in Fig. 23.

When the circuit of Fig. 18 is operated as just outlined, it is biased in such a manner that a portion of the collector voltage cycle occurs in the regenerative or negative resistance region of the transistor. As the oscillator enters this region, the internal collector impedance suddenly becomes smaller. This, in turn, will cause the rapid discharge of the collector capacitor in a positive direction as shown by the e_c curve of Fig. 23. Due to the suddenly increased collector current at the instant of regeneration, e_b increases rapidly in the negative direction. At this instant a negative pulse is formed at the emitter as a result of the negative base voltage swing. When the circuit leaves the regenerative region the collector current is substantially cut off. This abrupt change of the rate of flow of the collector current through the base inductance causes the base voltage to increase rapidly to a high positive value. The discharge of the collector capacitor carries the transistor outside of the regenerative region and the capacitor is again charged from the negative collector voltage supply. During the charging period of the capacitor the sinusoidal wave developed across the base circuit continues until a swing of the base sine wave in a negative direction coincides with a high negative collector voltage mutually to assist in driving the transistor into the regenerative region again and to initiate the next cycle. If the base voltage is sufficiently large to primarily determine the free-running frequency of the oscillator, a greater change of the collector bias voltage can be tolerated before frequency instability occurs.

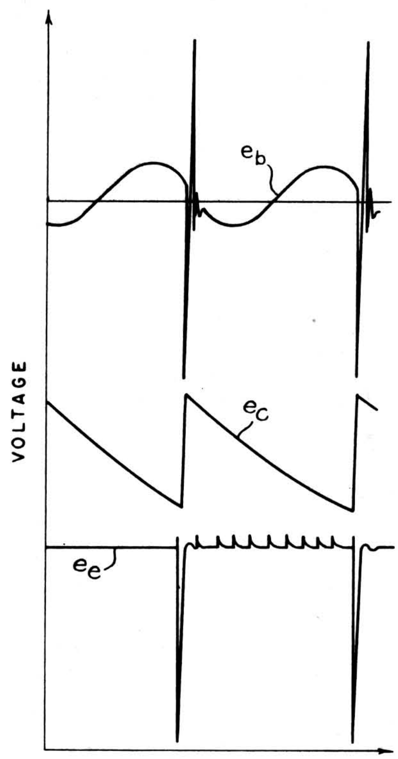

Fig. 23 - Voltage waves of the stabilized frequency divider of Fig. 18.

This suggests the desirability of utilizing such a circuit as a stabilized frequency divider where large division ratios are desired. Fig. 23 indicates the presence of synchronizing trigger pulses applied to the emitter. Such a circuit has proved to be most valuable in providing division ratios of as high as 10 or 20 to 1 over a wide variation of emitter and collector bias voltages. It must be kept in mind that the repetition rate of the synchronizing trigger pulses should substantially be an integral multiple of the oscillator frequency.

As previously published[12], separate RC networks may be connected to both emitter and collector and an LC circuit may be coupled to the base. In that case, both the emitter and collector voltages assume the shape of a sawtooth wave and the circuit may be synchronized by the application of positive pulses to the emitter or negative pulses to the collector or base. This relaxation oscillator may be further modified by replacing the RC emitter network by a resonant circuit connected to the emitter. The addition of such a timing circuit to the emitter enhances the stability of these oscillators.

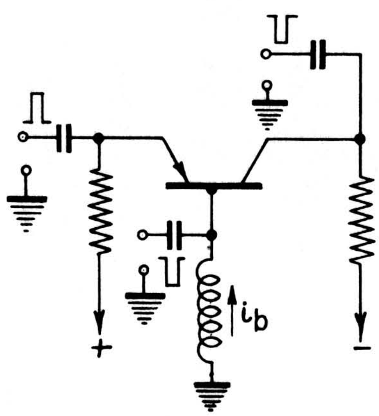

Fig. 24 - Triggered relaxation oscillator of the RL type.

A transistor RL relaxation oscillator has previously been reported.[13] Such an oscillator is illustrated in Fig. 24 and includes an inductor between base and ground. The period of oscillation is determined by the RL time constant circuit which includes the inductance of the base inductor and the resistance which appears looking into the base. The voltages e_b, e_e and e_c and the base current i_b are shown in Fig. 25, the latter being plotted so that an increase of i_b corresponds to an increase of the net current flowing from ground through the inductor to the base.

When the relaxation oscillator reaches the regenerative region, a steadily increasing base current i_b will flow which, in turn, will cause the base voltage to go initially in a negative direction. The resulting larger emitter current will drive the emitter voltage e_e also in a negative direction; e_c goes in a positive direction due to the larger collector current. The base voltage e_b depends on the current through the base inductor and is proportional to the negative derivative of base current with respect to time, $(-di_b/dt)$. Accordingly, as the value of the derivative decreases, e_b becomes less negative. Eventually, the base voltage becomes sufficiently positive to carry the circuit out of the regenerative region. This abrupt change of the base current derivative causes a positive voltage swing of e_b with a corresponding decrease of the emitter and collector currents. Consequently, e_e and e_c approach respectively their positive and negative supply voltages. Finally, e_b again decays exponentially at a rate determined by the RL time constant, eventually driving the oscillator into the regenerative region to initiate the next cycle of operation.

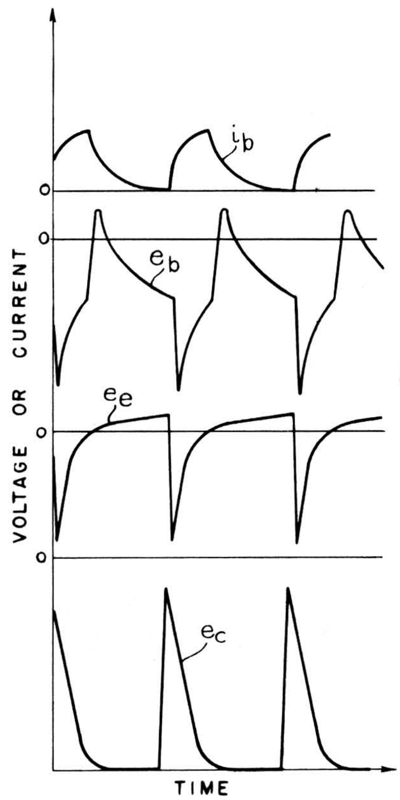

Fig. 25 - Wave shapes of the relaxation oscillator of Fig. 24.

Synchronizing pulses of positive polarity may be applied to the emitter or negative pulses may be impressed on base or collector as shown in Fig. 24. By appropriate choice of either the emitter or the collector voltage, the circuit of Fig. 24, as well as the circuits of previously described oscillators, may be made to be normally quiescent and may be triggered into the regenerative region by applying trigger pulses. The circuit of Fig. 24 may also be triggered by applying a sinusoidal wave to the emitter or base.

The RL relaxation oscillator of Fig. 24 will also function with a capacitor between collector and ground as shown in Fig. 26. The time constants of the RC and RL networks are chosen so that e_c and e_b will go simultaneously in a negative direction during each cycle of operation so that the collector and base voltages drive the oscillator concomitantly into the regenerative region.

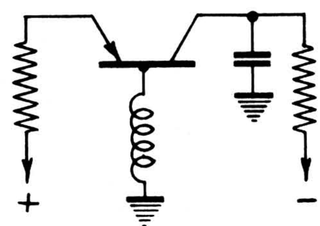

Fig. 26 - Modified RL relaxation oscillator.

The operation of the oscillator of Fig. 26 is essentially that described in connection with Figs. 24 and 25. However, the collector voltage is a saw-tooth wave. When the oscillator enters the regenerative region, the collector capacitor will be rapidly discharged to provide a large current through the base inductor. At this instant a highly negative voltage pulse is developed at the base by the inductive "kick" of the base inductor. Subsequently, the base current will increase at successively slower rates in the manner described earlier. As the rising base voltage carries the operation of the unit into the low current region, the base voltage increases sharply again to a highly positive value.

The oscillator of Fig. 26 is quite stable and can tolerate a substantial variation of the supply voltages without changing its repetition frequency. The oscillator may again be triggered or synchronized or it may be used as a frequency divider as long as the frequency of the synchronizing pulses is approximately an integral multiple of the free-running frequency of the oscillator.

One of the more desirable features of this circuit is its ability to develop very high amplitude voltage pulses as a consequence of the rapidly changing current through the base inductance. Voltage pulses of as high as 60 or 70 volts with a large value of the base inductance have been developed in this manner.

Values of the Circuit Parameters

The values of the circuit components in most of these oscillators are not critical, but a few remarks pertinent to their choice should prove helpful.

In the sine-wave oscillator circuits the values of components in the tuned circuits will, of course, be chosen to furnish the desired oscillation frequency. The resistances in series with the emitter and collector electrodes should be chosen to limit the peak currents to a safe value. In general, it is well to insert 100 to 1000 ohms in the emitter circuit, while a resistance of an order of magnitude higher should be inserted in the collector circuit. This latter resistance may be chosen in view of the voltage amplitude it is desired to generate at this point. It should be realized too that these resistances are degenerative, and if chosen too large, may cause a marginal transistor, that is, one with nearly unity current gain, to become inoperative. The base resistor, where needed in these oscillators, is chosen to assure sufficient regeneration. This resistor may have values between several hundred ohms and a few thousand ohms.

The base resistance in the relaxation oscillators must be chosen great enough to provide the highly regenerative type of operation. For this purpose, resistances of the order of 5000 ohms will usually prove sufficient, while an optimum value may be selected empirically.

The collector resistance-capacitance time constant, or the emitter resistance-capacitance time constant in the relaxation type of oscillator is selected primarily to provide the desired frequency of operation. However, the ratio of capacitance to resistance should usually be high. This enables the capacitor to furnish large surges of current for high amplitude voltage pulse generation while maintaining the d-c circuit resistance low enough to assure entry into the oscillatory region.

Richard O. Endres
RCA Victor Division

Raymond P. Moore, Jr.
RCA Victor Division

Edwin A. Oser

References

[1] Victor Gabel "The crystal as a generator and amplifier", *The Wireless World and Radio Review*, pp. 2–5, Oct. 1, 1924 and pp. 47–50, Oct. 8, 1924.

O. Lossev "Oscillating Crystals", *The Wireless World and Radio Review*, pp. 93–96, Oct. 22, 1924.

R. S. Ohl U. S. Patent 2,469,568 (Filed March 2, 1945).

[2] *Radio Craft*, Vol. 19, pp. 24–25, Sept. 1948.

C. E. Atkins, "A crystal that amplifies", *Radio and Television News*, Vol. 40, p. 39, Oct. 1948.

R. M. Ryder and R. J. Kircher, "Some circuit aspects of the transistor", *Bell System Technical Journal*, Vol. 28, pp. 367–400, July, 1949; Fig. 26a.

J. Bardeen and W.A. Brattain, U. S. Patents 2,524,035 and 2,586,597 (filed June 17, 1948); Fig. 12.

"Transistor Circuits" *Cornell-Dubilier Capacitor*, Vol. 15, pp. 3–7, Feb. 1950; Fig. 5.

[3] J. Bardeen and W. H. Brattain, "The transistor, a semi-conductor triode".

W. H. Brattain and J. Bardeen, "Nature of the forward current in germanium point contacts".

W. Shockley and G. L. Pearson, "Modulation of conductance of thin films of semi-conductors by surface charges", *Phys. Rev.*, pp. 230–233, July 15, 1948.

[4] W. M. Webster, E. Eberhard and L. E. Barton "Some novel circuits for the three-terminal semi-conductor amplifier", *RCA Review*, Vol. 10, pp. 5–16, March, 1949; Fig. 4.

[5] Ibid., Fig. 10.

"Transistor beat-frequency oscillator and amplifier", *Electronics*, Vol. 22, pp. 120, 122, Nov., 1949, and "Transistor et transistron", *La Technique Moderne*, Vol. 42, pp. 220–223, July 1 and 15, 1950, in Fig. 7 show, however, a different sine-wave oscillator where a parallel resonant circuit is connected to the collector.

Harold Heins "The germanium crystal triode", *The Sylvania Technologist*, Vol. 3, pp. 13–18, Jan., 1950; Fig. 9d.

[6] Webster, Eberhard and Barton, *op. cit.*, Fig. 10.

Ryder and Kircher, *op. cit.*, Fig. 26b.

Frank W. Lehan, "Transistor oscillator for telemetering", *Electronics*, Vol. 22, pp. 90–91, Aug., 1949; Figs. 2c and 3.

"Transistor Circuits", *Cornell-Dubilier Capacitor*, Vol. 15, pp. 3–7, Feb. 1950; Fig. 6.

Edwin Bohr and Hal French, "Tubeless oscillator covers audio to 2 Mc", *Radio-Electronics*, Vol. 22, p. 43, June, 1951.

[7] Ryder and Kircher, *op. cit.*, Fig. 26c.

[8] E. Eberhard and R. O. Endres U. S. Patent 2,570,436 (filed Sept. 30, 1949).

[9] Chance, Hughes, MacNichols, Sayre and Williams, WAVEFORMS, Massachusetts Institute of Technology Radiation Laboratory Series, 1949, pp. 110–122.

[10] A. J. Rack U. S. Patent 2,556,296 (filed April 26, 1949) illustrates in Fig. 9 a related oscillator circuit.

[11] Webster, Eberhard and Barton, *op. cit.*, Figs. 11–13.

E. Eberhard, R. O. Endres and R. P. Moore, "Counter circuits using transistors", *RCA Review*, Vol. 10, pp. 459–476, Dec. 1949; Figs. 9a and b.

[12] Eberhard, Endres, Moore, *op. cit.*, Fig. 11.

[13] *Ibid.*, Fig. 9c.