counted. If some other number is counted, the multivibrator is not locked-in on the correct submultiple of the control frequency but on a frequency found by dividing the control frequency by the number of "carrier spaces" in the series of harmonics:

$$f = \frac{F}{n} + 1 \qquad (6)$$

Where:
- f = multivibrator frequency,
- F = control oscillator frequency,
- n = number of multivibrator harmonics counted between adjacent control frequency harmonics (n+1 is the number of spaces between the harmonics.)

If the frequency of synchronization is incorrect, the setting of the variable resistor in the multivibrator must be changed.

Adjustments made to the variable resistor should result in abrupt changes of the multivibrator frequency, the harmonics abruptly changing their total number. If instead there is a smooth variation in frequency, the multivibrator is out of control and operating independently, and the control voltage must be increased. In the absence of control, it will also be noticed that the multivibrator harmonics are rough and wavering in character.

When the proper number of points are counted between the control frequency harmonics, a test may be made for positiveness of control by rotating the frequency-synchronization control back and forth over a small arc. This should cause no frequency change and is a good test for the appropriate control voltage level.

When the control voltage is of the proper value, it will be possible to switch the multivibrator on and off repeatedly without disturbing its controlled frequency.

* A Convenient Method for Referring Secondary Frequency Standards to a Standard Time Interval. L. M. Hull & J. K. Clapp. Proc. I.R.E., February 1929.

Beg Pardon...

If, due to our irregular and lagging publication dates, we have caused you to write and inquire; or, if we've given you the impression you've missed any issues of the AEROVOX RESEARCH WORKER, we're sorry.

Due to certain circumstances beyond the editors' control, publication dates have necessarily lagged.

Although this is the November 1940 issue, we expect to catch up within the next month, after which the AEROVOX RESEARCH WORKER will appear quite regularly — the month it is dated.

In the meantime, please bear with us a little while longer.

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The Aerovox Research Worker is a monthly house organ of the Aerovox Corporation. It is published to bring to the Radio Experimenter and Engineer authoritative, first hand information on condensers and resistances for radio work.

VOL. 12, NO. 11 NOVEMBER, 1940 50c per year in U.S.A. 60c per year in Canada

Theory and Operation of Multivibrators

By the Engineering Department, Aerovox Corporation

THE *multivibrator* is a unique form of relaxation oscillator first described in 1919 by H. Abraham and E. Bloch. The circuit was comparatively obscure for a number of years and has only lately become very well known for its part in measurements of radio frequencies, although J. K. Clapp proposed it for that present peculiar application as early as 1927.

As an oscillator, operated alone, the multivibrator is notoriously unstable. Its frequency is altered considerably by the slightest shifts in operating voltages or circuit values and its output-voltage wave form is characteristically ragged. Accordingly, it has little practical worth as an independent frequency generator.

However, the device has another noteworthy property which well adapts it to certain applications as we shall see later. It may readily be stabilized by injecting a small voltage of proper magnitude into its circuit from another stable oscillator. In the controlled state the stability and frequency accuracy of the multivibrator reach the same order as those properties of the controlling oscillator, and the emitted frequency becomes independent of small shifts in circuit values.

It is not required that the control oscillator frequency coincide with the fundamental frequency of the multivibrator circuit in order to obtain synchronization. The controlling frequency may be a harmonic or subharmonic. Multivibrators have been controlled experimentally by frequencies 40 to 50 times higher than their natural frequencies. In common present applications, the controlling frequency is harmonically related to the multivibrator fundamental (and generally held to a ratio of 10-to-1 for best results), so that the multivibrator presents the practical appearance of subdividing the control frequency. And it is in this role of *frequency divider* that the device enjoys its present wide acquaintance.

While frequency multiplication may be carried out simply by choosing the multivibrator fundamental equal to an integral *multiple* of the control frequency, this function is somewhat more satisfactorily performed by conventional multiplier circuits (doublers, triplers, quadruplers, etc.). However, it is interesting to note that harmonic frequencies may be obtained directly from the *harmonically-controlled* multivibrator. Even in the controlled state the multivibrator output voltage is rich in harmonics spaced equal to the multivibrator fundamental, several hundred of these being readily located with a sensitive detector. This harmonic series may extend far beyond the control frequency, subdividing spaces established by harmonics of the latter. Thus, when a 10-kc. multivibrator is controlled by a 100-kc. standard frequency oscillator in a modern frequency measuring assembly, prolific 10-kc. harmonics are provided to sub-divide equally the space between any two adjacent 100-kc. harmonics.

Aside from its radio-frequency applications, the harmonically-controlled multivibrator makes it possible to obtain precisely-known low frequencies from a stabilized higher-frequency oscillator. Thus, standard low frequencies extending down into the audio-frequency spectrum may be obtained from a satisfactory radio-frequency oscillator.

THE MULTIVIBRATOR CIRCUIT

The multivibrator circuit differs from other relaxation oscillators in its particular use of two triodes in cascade, yet resembles others in the absence of any inductance in the frequency-determining circuits, other than the small amount encountered as a circuit stray. It is entirely a resistance-capacitance oscillator.

The conventional multivibrator circuit of Figure 1 is seen to be essentially that of a two-stage triode resistance-coupled amplifier with the exception that the output circuit is coupled back to the input through the feedback condenser C_2. C_1 is the interstage coupling condenser; C_3 the plate-circuit by-pass condenser usually encountered in resistance-coupled amplifier circuits. The tubes A and B are identical in type and may be any suitable triodes. However, space may be conserved and replacement simplified by employing twin triodes 1G6-G, 1J6-G, 6A6, 6C8-G, 6E6, 6F8-G, 6N7, 6N7-G, 6SC7, 6Z7-G, 12SC7, 19, 53, or 79.

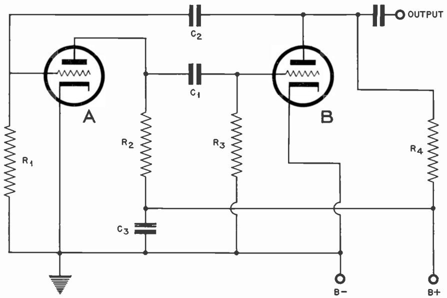

Fig. 1

The feedback provided by C_2 causes the uncontrolled circuit to "motorboat", or oscillate at a frequency determined by the plate- and grid-circuit resistances and capacitances and the tube characteristics. The time constants of the R-C combinations decide this frequency. The oscillations are the result of condensers charging and discharging through resistors, hence the wave form of the oscillatory currents is considerably distorted and therefore of large harmonic content.

If we neglect the presence of tubes, the multivibrator circuit is observed to be aperiodic. It is the function of one tube to sustain in that circuit periodic current variations of irregular wave form when excited by the other tube which provides the phase relation necessary to maintain the oscillations.

Because the fundamental frequency of oscillation is determined by the relaxation-oscillation time constant of the circuit, it is largely dependent upon the values of the coupling condensers, C_1 and C_2 and the grid resistors, R_1 and R_3. While there is no simple formula whereby the exact frequency of the combination may be calculated, a close approximation may be made from the following equation which takes into consideration the capacitances and resistances mentioned:

$$(1) \quad F = \frac{1000}{R_1C_2 + R_3C_1}$$

Where:
F = frequency in kilocycles,
C = capacitance in mfds., and
R = resistance in ohms.

For circuit simplification it is usual to choose C_1 equal to C_2 and R_1 equal to R_3, whereupon equation (1) becomes:

$$(2) \quad F = \frac{1000}{2RC} = \frac{500}{RC}$$

For any pair of identical fixed coupling condensers, the value of grid resistors required for a desired multivibrator frequency may be calculated by multiplying the sum of the capacitances in farads by the reciprocal of the frequency in cycles per second:

$$(3) \quad Rg = \frac{1}{f}(C_1 + C_2)$$

If, as above, the capacitances are chosen equal:

$$(4) \quad Rg = \frac{2C}{f}$$

The value of grid resistor may also be determined from the equation:

$$(5) \quad Rg = \frac{K}{C}$$

Where:

$$K = \frac{500}{f}$$

in this case -
Rg = grid resistance in ohms,
C = capacitance in mfds.,
f = frequency in kilocycles.

A number of grid resistor values which are required in order to obtain common multivibrator frequencies (100, 10, 1.0 and 0.1 kc.) with common condensers are listed for the experimenter's convenience in Chart A.

It has already been mentioned that the frequency formulas give only approximate results. Either the grid resistors or coupling condensers are made variable in order that the multivibrator frequency may be adjusted to a desired value. But since the capacitances in the circuit are generally of a large order of magnitude and therefore not easily varied; one of the grid resistors, or a portion of one, is usually made variable for this purpose. R_1, for example, might be composed of a fixed resistance in series with a variable, the sum of the two at some setting of the variable member being equal to the value indicated by equations (3), (4) or (5).

A practical example of 10-kc. multivibrator employed in several of the low-priced frequency standards now available to amateurs, servicemen, and others employs the two triodes of a 6N7 tube. In this circuit, C_1 and C_2 are each of 0.002 mfd. capacitance, R_2 and R_4 are each 2500 ohms, R_3 is 30,000 ohms, and R_1 composed of a 20,000-ohm fixed resistor connected in series with a 15,000-ohm rheostat (frequency control). The plate-circuit bypass condenser, C_3 is omitted. The fundamental frequency may be varied between approximately 8,000 and 12,000 kilocycles with the variable grid resistor.

SYNCHRONIZATION

Control of the multivibrator is effected by injecting an alternating voltage of suitable frequency and magnitude into the circuit, as previously described. The control voltage might be applied to the grid of tube A (Figure 1) through a sliding tap on the resistor R_1. The correct voltage for satisfactory synchronization might then be obtained experimentally by varying the position of this tap.

Better stability is obtained, however, when the control voltage is injected into the multivibrator plate circuit, preferably being developed across a common plate-circuit resistor as shown in Figure 2. R, is the common resistor interposed in the B-plus line. The plate circuit of the control oscillator (or amplifier) receives its operating potential from one end of this resistor, while the multivibrator plate circuit is connected to the adjustable tap in order that the proper amount of control voltage may be selected.

When the circuit values are fixed, the frequency emitted by the multivibrator progresses in distinct steps (jumping abruptly from one to the next highest in frequency) as the injected harmonic voltage is increased in magnitude. If, instead, one of the circuit values is varied, as outlined earlier, and the control voltage is held at a fixed value, similar frequency steps will result. If the control voltage is too low, the steps will not be present but the multivibrator frequency will be varied smoothly by adjustment of the variable component. It is this difference in frequency variation that quickly distinguishes the controlled from the uncontrolled state of operation.

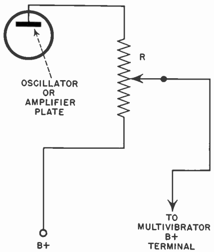

Fig. 2

If the operation of the device is checked (as, for example, by listening to one of its harmonics in a radio receiver), the uncontrolled signal will be recognized as very rough in character and continuously variable in frequency as the circuit is adjusted. When the control voltage is applied and raised to the proper value for satisfactory synchronization, the signal will at once become stable and will "step" in frequency as the circuit control is adjusted.

If the multivibrator fundamental frequency is low enough to be studied directly (as might be possible with earphones connected to the output), the uncontrolled signal, closely resembling a rough buzz with a tone component, will be noticed to clear into a clean tone in the controlled state. For best synchronization, it will be noted that the multivibrator fundamental should be set somewhat lower than the desired controlled frequency.

CHART A

C (Mfd.)	Grid Resistance (in Ohms) 100 Kc.	10 Kc.	1 Kc.	0.1 Kc.
.001	5000	50,000	500,000	
.002	2500	25,000	250,000	
.003	1666	16,666	166,666	
.004	1250	12,500	125,000	
.005	1000	10,000	100,000	
.006	833	8,333	83,333	
.007	714	7,142	71,428	
.008	625	6,250	62,500	
.009	555	5,555	55,555	
.01	500	5,000	50,000	500,000
.02	250	2,500	25,000	250,000
.03		1,666	16,666	166,666
.04		1,250	12,500	125,000
.05		1,000	10,000	100,000
.06		833	8,333	83,333
.07		714	7,144	71,444
.08		625	6,250	62,500
.09		555	5,555	55,555
.1		500	5,000	50,000
.2		250	2,500	25,000
.3			1,666	16,666
.4			1,250	12,500
.5			1,000	10,000
.6			833	8,333
.7			714	7,144
.8			625	6,250
.9			555	5,555
1.0			500	5,000
2.0			250	2,500

Listings have been omitted where resistance values are at such high or low extremes that positive adjustment of the circuit becomes difficult.

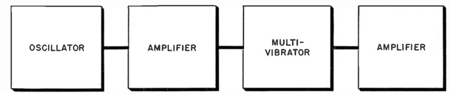

Fig. 3

In order to isolate the control oscillator from multivibrator circuit disturbances, it is recommended that one or more untuned, resistance-coupled *tetrode* or *pentode* amplifier stages be inserted between the oscillator and multivibrator, as indicated in Figure 3. A similar isolating amplifier is shown following the multivibrator to protect the latter from output-circuit disturbances. This last amplifier may be highly biased to accentuate the higher harmonics that are extremely useful for radio-frequency measurements.

Action of the injected control voltage is not the same for even and odd frequency ratios. If the multivibrator circuit is symmetrical, wave symmetry tends to restrict positive control to the even ratios. Hull and Clapp* have suggested circuit asymmetry for stable operation and positive control with both even and odd ratios. There are a number of ways of arriving at satisfactory asymmetry but the most pleasing is perhaps their system of making the plate resistor R_2 (see Figure 1) ten to fifty times larger than R_4. Preserving this ratio, the plate resistance should be kept low for ease in selecting the operating frequency.

There is an optimum value of control voltage for the best synchronization and this is slightly more than the minimum value required for frequency "stepping" to the desired fundamental. When the multivibrator is satisfactorily controlled, the variable synchronizing resistor may be varied over a small arc of rotation without encountering adjacent frequency steps. While it will be found possible to keep the multivibrator "locked" on steps other than the particular frequency for which it was designed, it is recommended that operation be restricted to that frequency most closely approximated by the R-C values.

PRACTICAL CONSIDERATIONS

For the most reliable operation, C_1 and C_2 should be first-grade mica condensers (whenever the capacitance permits) obtained as near as possible to the values arrived at by calculation. They should be mounted below the instrument chassis away from the heat of tubes and close to their points of connection.

As far as practicable the triodes should be matched in characteristics, particularly as regards inter-electrode capacitances. Certainly there must be no wide tube differences, if performance with matched circuit values is expected.

The various resistors should be of not less than 2-watt rating for any of the receiving type triodes operated at 250 volts, or less, plate potential. The variable resistor used as a frequency-synchronization control should be a regulation wire-wound type of the best quality and must have a maximum value not exceeding 50 percent of the total resistance calculated for the leg in which it is inserted.

The plate power supply should incorporate voltage regulation for greatest stability of the multivibrator and control oscillator-amplifier. The current requirement of multivibrator arrangements, such as described in the foregoing paragraphs, is relatively low so that simple voltage regulator circuits should be adequate.

For most positive control, the oscillator-multivibrator frequency ratio should not be carried beyond 10-to-1 in a single multivibrator stage.

Switching operations in the multivibrator stage should be accomplished in such a manner as to place a varying load on the control oscillator (if plate-supply voltage regulation is not used), since such variations will react unfavorably on the oscillator frequency. The multivibrator may be switched off by a short-circuiting switch connected between one triode grid and ground, thus leaving the plate current undisturbed.

PRACTICAL ADJUSTMENT

One of the most satisfactory methods of checking the multivibrator frequency consists in tuning through a series of its harmonics with a calibrated radio receiver operated as near the frequency of the control oscillator as possible. The additional harmonics lying between any two adjacent harmonics of the control oscillator are counted to determine the frequency of the multivibrator.

Assume, for example, a 10-kc. multivibrator controlled by a 100-kc. standard frequency oscillator. With the multivibrator switched off, any two adjacent harmonics of 100 kc. are located on the receiver dial and their positions noted. The multivibrator is then switched on, whereupon its harmonics will appear as equally-spaced, *stable* signals between the two 100-kc. harmonics. If the multivibrator frequency is exactly 10 kc., as intended, nine such points may be

(*Continued next page*)