



Design Notes on the Resistance-Capacity Oscillator Circuit

Part I

OVER a period of years the Hewlett-Packard Company has been requested to design and manufacture a large number of special-purpose resistance-capacity oscillators having such characteristics as compressed or expanded scales, unusually wide frequency range, high power output, high and low frequencies, special controls, etc. The following will describe some of the con-

siderations involved in the design of the resistance-capacity circuit.

Briefly, the resistance-capacity oscillator circuit consists of a two-stage amplifier having both negative and positive feedback loops (Figure 2). The positive loop causes the circuit to oscillate and includes the resistance-capacity frequency-selective network which gives the circuit its name.

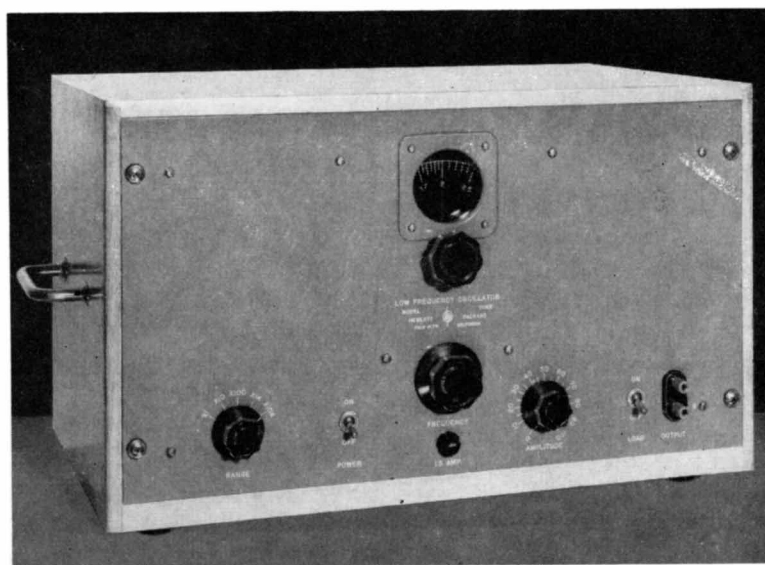


Figure 1. Model 202B Low Frequency Oscillator Covering Frequency Range from $\frac{1}{2}$ to 50,000 cps.

THE "resonant" frequency of the RC network is given by the well-known expression $f_c = 1/2\pi RC$. The negative feedback loop stabilizes the operation of the circuit by minimizing phase shift and confining operation to the linear portion of the characteristics of the tubes. One element of the negative feedback circuit is a non-linear ballast resistance which limits the amplitude of oscillation. The ballast element adjusts its resistance either higher or lower so as to compensate for any tendency of the oscillations to vary in amplitude. If the non-linear element is located in the cathode circuit, as in

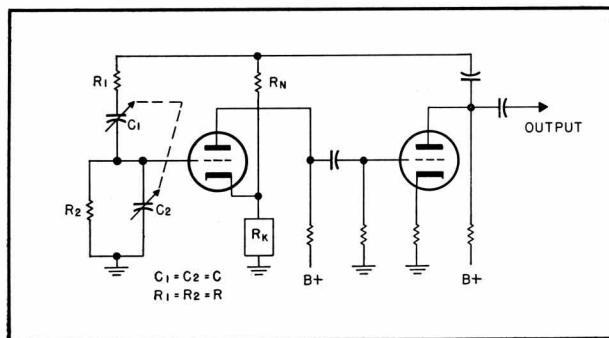


Figure 2. Basic Circuit of Resistance Capacity Oscillator

Figure 2, it must have a positive temperature coefficient. However, a negative temperature coefficient element also can be used, in which case the positions of R_k and R_n in Figure 2 would be reversed.

The resistance-capacity oscillator is commonly tuned with a tuning capacitor rather than a variable resistance because of the smooth frequency control and long life obtainable with such capacitors. Since the frequency of oscillation of the circuit is inversely proportional to the capacity C in the frequency-determining network (instead of to the square root of the capacity as in an LC oscillator), the RC oscillator can be made to cover a tuning span as wide as the capacity variation in a tuning capacitor. Thus, 10:1 frequency variations in a single sweep are easily obtained and it is customary to design the circuit to operate over 10:1 bands. A number of bands can be used with one circuit by changing the pairs of resistances in the frequency-determining network.

FREQUENCY RANGE

The resistance-capacity oscillator is inherently a wide-range oscillator and it is possible to design circuits to operate over a 100,000:1 frequency range in five 10:1 bands without undue loss of the desirable characteristics of the oscillator. At both the high and low ends of the range of such a circuit, however, some loss in performance does occur. In both cases this loss is the result of phase shift, a characteristic to which the

circuit is very sensitive. At the high frequency end of the range, the phase shift is introduced in the form of a lagging phase characteristic for the amplifier portion of the oscillator. The effect of this lag is that at a given setting of the tuning capacitor the frequency of oscillation is lower than that predicted by the "resonance" formula. This error occurs because the circuit must oscillate at a frequency for which the phase shift around the closed positive feedback loop is an integral multiple of 2π radians. Thus, if the amplifier shifts phase by $-\Delta\Phi$, the frequency of oscillation must shift to a lower frequency where the frequency-determining network will contribute a phase shift $+\Delta\Phi$ (Figure 3). In the usual multi-range oscillator the lag in phase results in an increasing error in calibration as the oscillator is tuned to the higher frequencies. This effect can be compensated to a degree, but the differences in individual instruments introduce capacity variations that limit the amount of practical compensation. It is interesting to note that a phase shift of only a fraction of a degree will cause calibration errors in the order of 1%, whereas in an amplifier the commonly used "3-db point" introduces a phase shift of 45 degrees.

At the low frequency end of the range the phase shift is introduced by the coupling capacitors, resulting in a leading phase characteristic for

the amplifier. Consequently, at the lower frequency region of oscillation the actual frequency is higher than that predicted by the "resonance" formula.

In special cases it is possible to make use of these phase shift effects to obtain specific characteristics. For example, the amplifier can be intentionally given a lagging angle at low frequencies in order to increase the range of the circuit. Such an arrangement is shown in Figure 4 where a series RC network is connected across the amplifier output. By properly proportioning R and C , it is possible to increase the continuous sweep of the oscillator from 10:1 to more than 30:1. However, this range extension causes some deterioration of the performance of the circuit because of the load placed on the oscillator at the higher frequencies. This effect will be described in more detail later.

The above phase shift effects occur in the oscillator itself. Ordinarily, an isolating amplifier is used following the oscillator and this amplifier introduces some further limitations, mostly in applications where it is necessary to use an output transformer for power or balanced-load reasons. The presence of an output transformer usually reduces the desirable frequency range of the oscillator to a range of about 1000:1.

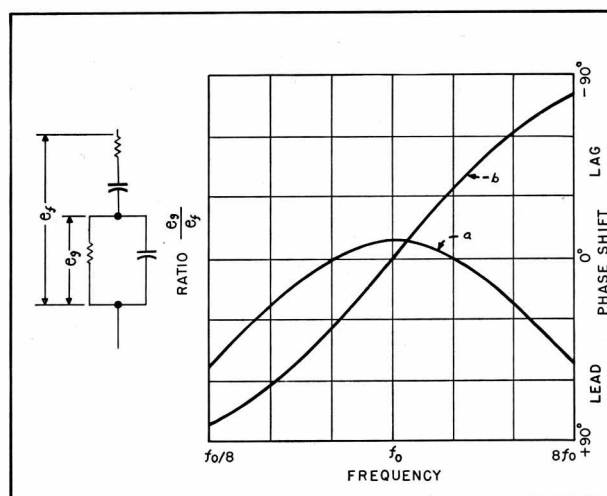


Figure 3. Frequency (a) and Phase (b) Characteristics of Frequency Determining Network

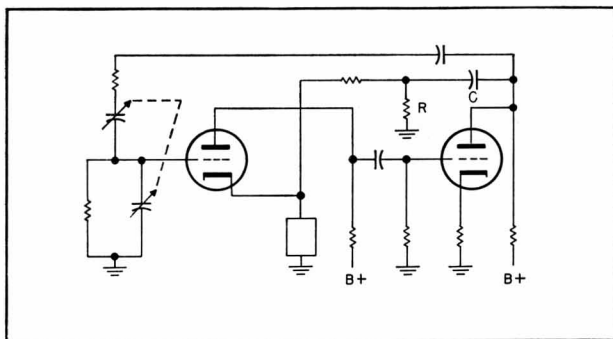


Figure 4. Circuit for Increasing Frequency Range of Resistance Capacity Circuit

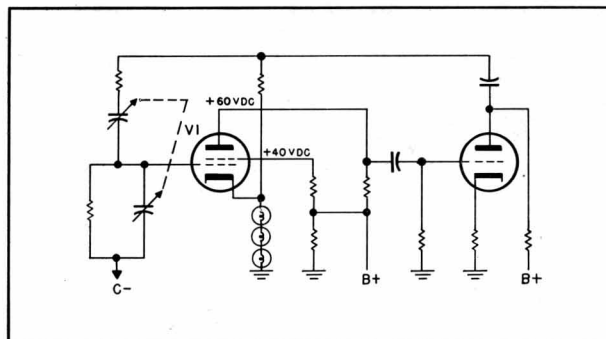


Figure 5. Circuit for Low Frequency Oscillator

LOW FREQUENCY OSCILLATORS

Circuits have been developed to permit the operation of the resistance-capacity oscillator at frequencies below one cycle per second and higher than one megacycle per second. However, it has not been practical to operate any one circuit over such a wide range.

In low frequency resistance-capacity oscillators one of the limiting factors is the operation of the ballast element in the negative feedback circuit. The most satisfactory ballast element from the standpoint of performance and cost is a small incandescent lamp. As used in higher frequency oscillators, the lamp will operate quite well down to frequencies corresponding to the low end of the audio spectrum. However, the thermal time constant of the lamp is such that at lower frequencies the lamp resistance tends to change in accordance with the variations in amplitude of the individual cycles of oscillation. This effect results in severe distortion of the output waveform. Therefore, it is necessary to obtain a ballast element having relatively greater thermal inertia.

One solution is the use of certain types of negative temperature coefficient thermal resistors. However, tests on these devices indicate that their resistance varies widely with normal variations in ambient temperature within the oscillator cabinet, causing undesirable variations in performance.

A more satisfactory arrangement for obtaining the necessary thermal characteristics for low frequency operation is shown in Figure 5. The operating voltages on the tube electrodes are low so that a minimum of space current is drawn through the lamp in the cathode circuit. In addition, fixed bias is used on the control grid as aid in minimizing gas current. This arrangement allows the lamp to operate well down to frequencies as low as a fraction of a cycle per second because of the decrease in radiation from the lamp. Although the lamp is never operated where visible light is emitted, radiation nevertheless accounts largely for the cooling of the lamp. Since radiation is influenced by the fourth power of the lamp filament temperature, a lower operating level results in relatively higher thermal inertia. In actual practice three lamps in series are used to obtain the necessary value of resistance.

The operation of the resistance-capacity circuit at such low frequencies introduces an additional problem. Using tuning capacitors that are commercially available, the resistance values that are necessary to satisfy the "resonance" formula are in the order of 1 to 10 megohms for audio frequencies. However, at lower frequencies the resistance values become prohibitively high. For example, with a 1000-micromicrofarad capacitor the value of R for an oscillation frequency of 1 cps is approxi-

mately 160 megohms. Considering that the insulation resistance must be large compared to the frequency-determining resistance, it can be seen that both the input impedance of the tube and any leakage paths would affect the circuit.

In order to circumvent this stringent requirement, it is necessary to operate the circuit with several tuning capacitors in parallel. The impedance level of the circuit is inversely proportional to the number of capacitors used, making necessary the use of four or more standard four-gang capacitors to obtain the required capacitance in variable form. Through the use of this system it is possible to reduce the resistance values in the frequency-determining network to 40 megohms for one cycle per second operation and thereby to achieve lower insulation levels accordingly.

HIGH FREQUENCY OSCILLATORS

The higher frequency limit at which the resistance-capacity oscillator can be operated satisfactorily is determined primarily by the plate loading on the second tube of the oscillator. As can be seen from Figure 2, both the positive and negative feedback circuits load the plate of the second tube. The negative feedback loop constitutes a low-impedance load of about 4500 ohms on the tube. The impedance of the positive feedback loop decreases as the frequency is increased and is in the

order of 3000 ohms at a phase angle of 45 degrees at one megacycle. These two loads are in parallel and the combination is in parallel with the plate feed resistor for the tube. This reactive and low-impedance loading reduces the gain of the circuit at high frequencies and introduces serious phase shift. As a result, the distortion increases and errors in calibration arise at the higher frequencies.

The above effects can be reduced by several methods. First, the gain of the second stage of the oscillator is kept high by the use of tubes with very high transconductance. Also, in some applications it is practical to reduce the capacity of the tuning capacitor and thereby achieve a higher impedance for the frequency-determining network. However, the limit to such reduction is determined by the stray capacity in the grid circuit of the first oscillator tube. This stray capacity is in parallel with part of the main tuning capacitor and therefore determines the minimum possible capacity in the frequency-determining network. Variations in this stray capacity will change the frequency of oscillation of the circuit. Therefore, it is desirable to minimize this effect by adding other fixed capacities in parallel with the stray capacity so that the strays constitute only a fraction of the minimum capacity. In order to have a tuning span of 10:1, it is necessary that the maximum capacity of the tuning capacitor be ten times as great as the sum of the capacities constituting the minimum capacity. These factors set a limit to which the impedance of the frequency-determining network can be increased for a given frequency of oscillation and tuning span.

At the higher frequencies the reduced gain of the oscillator and consequent reduction in negative feedback make the oscillator circuit more

susceptible to drifts and variations caused by tube aging and supply voltage changes. As a result, it is common practice to operate the circuit from a regulated plate supply when the circuit is to be used at frequencies higher than approximately 150 kcs.

The above factors combine to limit the top practical frequency of the resistance-capacity oscillator to the order of one megacycle. However, the circuit will oscillate at frequencies of several megacycles.

DISTORTION

The resistance-capacity oscillator inherently is a generator of low distortion voltages owing to the negative feedback circuit and to the fact that the circuit is what might be termed a Class A oscillator.

The purity of the generated voltage is limited by the linearity of the transfer characteristics of the tubes. With proper operating voltages on the tube electrodes, the circuit will generate voltages having in the order of $\frac{1}{2}$ of 1% distortion, even with individual tubes that differ considerably from the average tube characteristic. By the selection of suitable individual tubes of the type used in the circuit, distortion can readily be held to less than $\frac{1}{4}$ of 1%. This figure is the order of the practical limit of distortion obtainable from the circuit over the sub-audio to middle ultrasonic frequency range.

The distortion obtained under these circumstances is mainly third harmonic. Second harmonic distortion is minimized by adjusting the dc voltages on the tube electrodes so that the second harmonic distortion generated by one tube of the oscillator is partially cancelled by the curvature of the other tube's transfer characteristic.

For applications requiring less than $\frac{1}{4}$ of 1% distortion, a frequency-selective amplifier can be used fol-

lowing the oscillator to eliminate some of the distortion generated by the oscillator. In these cases the tuning of the amplifier is variable and is tracked with the tuning of the oscillator in a manner similar to the system used between the oscillator and tuned rf amplifiers in a radio receiver. However, in the resistance-tuned application the selectivity of the amplifier is controlled by RC circuits which select only the harmonic voltages and apply them to the amplifier input as negative feedback. This system reduces the harmonics in the generated voltage without affecting the fundamental, resulting in an amplified voltage that has less distortion than the amplifier driving voltage. Practical reductions of 10 db in distortion over the major portion of the audio spectrum are possible with this arrangement.

In low frequency oscillators the distortion requirements usually are not as severe as in the audio and low ultrasonic regions. However, at frequencies as low as one or two cps it is possible to obtain distortions in the order of 1% with the high thermal inertia circuit (Figure 5) described above.

In high frequency oscillators of 50 kcs or more, the resistance-tuned circuit generates less than 1% distortion up to frequencies of several hundred kilocycles. At frequencies higher than this, the distortion increases rather rapidly owing to the heavy loading of the positive feedback network on the plate of the second oscillator tube and the consequent loss of negative feedback. As a result distortion is in the order of 4% at frequencies of one megacycle.

—Brunton Bauer.

The above is the first part of a two-part article by Mr. Bauer. The article will be concluded in an early issue of the *Journal*.

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