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VOLTAGE-CONTROLLED ELECTRONIC MUSIC MODULES

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Electronic music, as the term is understood to mean at the present time, is the class of musical compositions either created solely by electronic means, or utilizing sounds which have been heavily processed electronically. The electronic composition is recorded, then presented to the listener as pre-composed sound, conceived and performed by the composer.

The wide variety of sounds which can be readily produced electronically but are impossible to produce through conventional musical instruments offer the composer an enormous variety of new musical effects and elements of composition. In addition, the composer is able to arrange the sounds exactly as he wishes,— to "compose" the music in the most literal sense. The composer pays heavily for these added advantages. With a mulitplicity of sound parameters under his control, the composer must become adept at manipulating his electronic apparatus so it will produce the desired results. The programming and manipulating of much of the electronic music equipment currently in use tends to become laborious and time-consuming. In the larger studios, it is possible to program the parameters of each sound by a digital code, then "play" the entire composition by means of a series of decoding, generating, and processing circuits[1] or by utilizing a digital computer in conjunction with a digital-to-analog converter.[2] Smaller installations generally consist of conventional test instruments, electronic laboratory equipment, and standard high-fidelity sound reproducing apparatus. The installation is arranged in a convenient manner and simple modifications on some of the instruments are made.[3,4] In these studios, single sounds or smaller groups of sound are individually programmed and recorded, and the many individual tape segments are then spliced to form the complete composition.

The motivation of the present work is the premise that the electronic music composer will benefit having at his disposal a sound apparatus which he can easily understand, quickly set up, and "play" spontaneously, more in the manner of a conventional musical instrument than of a code-controlled apparatus. (This premise has yet to be tested at length). The system to be described consists of (a) voltage-controlled signal generating and processing modules and (b) a variety of transducers designed to produce voltages proportional to the position, velocity, and force of the musician's hands. Particular stress has been placed on attaining a linear variation of the properties of the modules with respect to the control voltage's magnitude, a feature which enables the modules to be programmed according to simple rules.

The development of "electronic musical instruments" is certainly not a new field. The theremin, still the most original and novel of electronic musical instruments, was invented in 1920, and achieved a brief commercial success in this country during 1929. Another instrument invented by Leon Theremin was his "electronic cello", a voltage-controlled oscillator, whose control element was a potentiometer, wound on a straight mandrel. Two prewar monophonic keyboard instruments, the Trautonium, and the Ondes Martenot, both permitted the performer to introduce subtle variations in the pitch and attack of the tone. Finally, the Solovox was the first wholly electronic commercial instrument in this country to fully exploit the tonal variety associated with changes in harmonic structure.

The failure of any of these instruments to attain widespread success can be attributed at least partially, to the limitation on the degree of control which the performer is able to exercise over the instrument's sounds. Thus, for instance, none of the aforementioned instruments enable the performer to make continuous changes in the harmonic structure. More recently, the problem of matching a set of electronic musical instrument control mechanisms to a musician's potential capabilities has been investigated through experimentation with touch-sensitive mechanisms designed to control all of the important parameters of a musical tone.[5] However, much work in this field remains to be done, as evidenced by the fact, at the present time, no original electronic instruments enjoy even moderate success.

On the other hand, the rising popularity of electronic music suggests that the wide versatility of a studio of functional components is musically valuable. A compatible system of modular components, some of which are voltage-controlled, has been shown to be useful in coordinating electronic sounds with those of a conventional musical instrument.[6] The main feature of the modules to be described is the systematic use of voltage control, thus permitting the application of control transducers most suited to the music to be produced.

VOLTAGE-TO-CURRENT CONVERTER

Figure 1 shows the circuit of a balanced-input D.C. amplifier with multiple current outputs. The output current is kept linear by comparing the controlling voltage E_{in} with the voltage drop across a fixed resistor. The error signal at the output of the difference amplifier is amplified further, and then applied to the bases of two or more matched PNP transistors, each of which has a 2.5K precision resistor in series with its emitter. The voltage to which E_{in} is compared is taken across a 2.5K resistor in series with the collector of the first PNP output transistor. When connected to approriate loads, the remaining current outputs will "follow" the collector current of the first transistor. The gain I_c/E_{in} of the circuit shown in 0.4 ma/volt. The output current varies linearaly with the collector current to within 1µa. down to approximately 5µa. This bottom limit is determined by the Ico of the output transistor.

Temperature stability is achieved through the use of a balanced difference amplifier, and silicon amplifier transistors. When the two differential amplifier transistors are mounted in a common heat sink, no temperature effects in the range 10°-$40^{\circ}C$ are observed,except for the raising of the bottom limit of the output current. This effect can readily be reduced by either using silicon output transistors, or applying a bias to permit the output transistor base current to reverse.

The circuit shown in Figure 1 supplies plus-to-minus currents which are directly proportional to a positive input voltage. By modifying the output transistor arrangement, it is possible to obtain minus-to-plus output currents. Also, by placing non-linear resistances in the emitter circuits of one or more output transistors, it is possible to tailor the linear relation between E_{in} and I_c to correct for small spurious effects in the remaining control circuitry.

The D.C. amplifier with multiple current outputs is used to drive the variable frequency oscillator and the variable gain amplifier.

VARIABLE FREQUENCY OSCILLATOR

In the variable frequency oscillator module, the control current is used to charge the capacitor in a unijunction relaxation oscillator. Susbsequent wave shaping circuitry provides a variety of output waveforms, each of which is musically useful.

Figure 2 shows the complete circuit of the oscillator module. The emitter voltages at which the unijunction fires and switches off are both dependent primarily on the supply voltage, and only to a very small extent upon temperature or average emitter current. Thus, if the supply voltage is regulated, the frequency of oscillation of the unijunction will be proportional to the rate of capacitor charge, which in turn, is proportional to the control current and inversely proportional to capacitance. The control current must be much larger than the minimum emitter current required to fire the unijunction (typically 1 ua) but less than the current at which the emitter will conduct continuously (typically 5 ma).

Thus, a two decade frequency range can be easily gotten merely by varying the oscillator control current within the above limits, and a 3 decade range can be achieved with some loss in frequency/control current linearity. The total range of the oscillator may be extended by switching in a variety of charging capacitors. The circuit in Figure 2 is capable of a maximum frequency of 6 KC with a control current input of 1 ma and .015 charging capacitor. The four highest ranges are spaced an octave apart from each other. The 2.4 MF capacitor gives a frequency range of .02-5 cps, and is useful in timing and modulation applications.

The unijunction emitter is isolated by an emitter follower, which drives the first wave shaper. This first wave shaper consists of a transistor with large resistances in series with both its emitter and collector. The effective values of each of these resistances are the same, and the bias conditions are set so that the transistor saturates exactly at the mid-point of the applied sawtooth. Thus, the emitter wave-form is still a sawtooth, but the collector is now triangular, with a narrow spike corresponding to the discharge portion of the sawtooth. Figure 3a shows the wave-form at the collector, and Figure 3b is the wave-form after filtering by capacitor C1 and C2. A small bump in an otherwise perfect triangular wave remains. This bump, while audible, does not detract substantially from the characteristic mellow, flute-like timbre of the triangular wave.

Both the sawtooth wave at the emitter and the triangular wave at the collector of the first wave shaper are applied to emitter followers for further isolation. The sawtooth output is further applied to a clipping transistor, which switches abruptly from the non-conducting to the saturated state. A rectangular pulse wave appears at the collector of this transistor, the pulse width being determined by the portion of the exciting sawtooth at which the clipping transistor switches. The PULSE WIDTH control in Figure 2 varies the pulse width from 10% to 50% of the period.

The entire oscillator module is direct coupled, thus permitting arbitrarily slow oscillations. Furthermore, each output is biased so that the extreme negative portion of the waveform is at ground potential. This allows any of the output wave-forms to be used directly as control voltages for other modules.

The control voltage / frequence linearity of the D.C. amplifier and oscillator modules combined is shown in Figure 4. The deviation at the lower frequencies can be attributed to the unijunction emitter current, while the high frequency flatness is due primarily to the non-zero unijunction discharge time. This time is about 20μsec. for a wide range of charging capacitors, and is relatively independent of temperature and average emitter current.[7] Without any compensation for either of these effects, a range of 4 octaves may be obtained, the top and bottom notes of which are only 10 cents (0.1 semitone) flat, when a voltage proportional to the desired frequency is used to control the D.C. amplifier-oscillator combination.

VARIABLE GAIN AMPLIFIER

In the oscillator described above, the operating points of the active elements remained essentially constant with changing frequency. The variable gain amplifier to be described, on the other hand, uses the linear dependence of the dynamic resistance of the emitter-base diodes of a pair of transistors upon the diode current as the variable-gain mechanism. In the range of current normally employed in transistor circuitry, the emitter-base diodes of the 2N2926 silicon transistors behave very nearly like ideal diodes. The dynamic resistance of an ideal junction diode is

$$r = \frac{kt/e}{I_c}$$

where k = Boltzmann's Constant, T = absolute temperature, e = electronic charge and I_c = diode current[8]. "k" and "e" are fundamental physical constants. In an electronic music studio, T is not likely to change more than 1% during a working session. Thus, the dynamic resistance of a junction diode in its "ideal" region is capable of accurate and predictable behavior.

Figure 5 shows the circuitry of the variable gain amplifier module. The portion of the circuit drawn in solid lines is the basic amplifier; the dashed-line portions are buffer circuitry, the applications of which will be described in the next section. We will be concerned only with the basic amplifier in this section.

The basic amplifier is balanced throughout to reduce distortion and provide for effective isolation of the control current from the signal current. The first stage is essentially a current amplifier, loaded almost entirely by the 5 ohm resistor between the emitters of the second stage. This simple arrangement provides the floating signal voltage which drives the second (control) stage. The control stage is connected on the common base configuration. Nearly all of the signal current flowing into the emitters will emerge from the collectors. The control current determines the emitter-base dynamic resistance, and therefore the signal current flowing into the emitters. To a first approximation, the current gain of the control transistors do not affect the gain of this stage. The linear relationship between control current and gain breaks down only when the dynamic resistance of the base-emitter diodes approaches the 5 ohm load resistance. Figure 6 illustrates the range of linearity of control current/gain. At I_c = 2ma, the gain is about 10% low. Applying the above expression for dynamic impedence, we find that the dynamic resistance of the two emitter-base diodes in series is 5 ohms when the current per emitter is 1 ma. Thus, the loading of the 5 ohm resistor by the emitter-base diodes reduces the emitter-to emitter signal voltage by 10%, and can wholly account for the departure of the control current/gain characteristic from linearity.

The final balanced stage of the variable gain amplifier serves only to reduce the common-mode (control) signal. The variable BALANCE rheostat is set for minimum control signal at the output.

The specifications of the basic variable-gain amplifier module are given below:

1. Input Impedence:	800 ohms
2. Output Impedence:	6,000 ohms
3. Max. Voltage Gain:	100
4. Range of Voltage Gain:	greater than 80 db
5. Gain range in which gain is directly proportional to control current to within 10%:	.1 - 100 (60 db)
6. Gain range in which gain is directly proportional to control current to within 1%:	.1 - 10 (40 db)
7. Signal-noise ratio at voltage gain of 50 and input voltage at 5 mv:	better than 70 db
8. Signal-noise ratio at voltage gain of .05 and input voltage of 5 mv:	Better than 20 db
9. Maximum voltage input:	10 mv
10. Total harmonic distortion at maximum gain and input voltage of 10 mv:	1.6% (mostly second harmonic)
11. Frequency response:	Lower limit depends only on size of coupling capacitors. Upper limit is greater than 20 KC.

The above specifications were achieved without selecting matched transistors, and using only carbon composition resistors. The signal-to-noise ratio could be improved by using low noise transistors, while the use of matched resistor and transistor pairs would further reduce the amount of control current variation reaching the output.

The buffer input stage shown in Figure 5 raises the input impedance to approximately 100 K. The buffer output stage offers two outputs, one low impedance output (Eo) with 200 ohm impedance, and one high impedance output (Io) with approximately 50 K impedance. These buffer stages are required for a large class of applications, some of which will now be described.

THE VARIABLE GAIN BLACK BOX: VOLTAGE- CONTROLLED FILTERS

The variable gain amplifier module has the following important features:

1. The input and output impedances remain constant for all values of control current, and

2. Control current variations produce no corresponding signal at either the input or the output.

Thus, in using the variable gain amplifier as a circuit element, only the input impedance, output impedance, and gain need be specified. A general symbol for this variable gain circuit element is shown in Figure 7a. One input and four independent outputs (2 current outputs and 2 voltage outputs) are shown. (Four independent outputs are achieved by connecting two output buffer stages to the output of the basic variable gain amplifier).

If the feedback path from one of the current outputs to the input is provided, then the output impedance may be either resistive or reactive, and will depend upon the amplifier gain. Elementary circuit analysis will reveal a limitless variety of filters and oscillators which may be assembled with variable gain amplifier modules. The simplifying assumptions listed in Figure 7a are used to derive the equivalent circuits shown in Figures 7b, 7c, 7d. The low pass filter in Figure 7b uses a capacitor in parallel with the amplifier output. The feedback network gives the amplifier a resistive output, the magnitude of which is inversely proportional to the gain. The network is fed from a current source. At low frequencies, all of the input current flows through the"resistor" and at high frequencies, all the current flows through the capacitor. The second current output follows the "resistor" current, and may be used to feed another filter requiring a current input.

The high pass filter in Figure 7c uses a large resistor in series with the output of a variable gain amplifier whose feedback elements give it an inductive output impedance. Because the phase shift from output to input is not exactly 90^{o} in this circuit, the "inductance" of the amplifier output has an effective series resistance.

The bandpass filter in Figure 7d uses a variable gain amplifier connected to give an inductive output impedance, in parallel with a fixed capacitor. The center frequency of the resonant circuit is proportional to the square root of the amplifier gain, and the circuit Q is proportional to the center frequency. Thus, for an input signal with uniform energy per cycle (e.g. white noise), the energy output of the bandpass filter will be independent of the center frequency.

The three simple applications of the variable gain amplifier shown in Figure 7 are simple examples of the capabilities of the variable gain amplifier when used as a voltage-controlled passive circuit element. Networks to provide a wide variety of electrical characteristics can be assembled. For instance, three low pass filters can be connected in tandem to form a 3-section R-C low pass filter. Then, by connecting a feedback loop around all three low-pass sections, a variable frequency phase shift oscillator can be set up. With an appropriate amplitude limiter, the output of this oscillator will be sinusoidal, and to a first approximation, the amplitude of the oscillation will be independent of frequency. As another example, several low pass filters can be connected in tandem with several high pass filters. With the cutoff frequency of the low pass sections above that of the high-pass sections, a bandpass filter is formed. Either the low or the high cutoff frequency can be proportional to the control voltage, or they can be varied together from the same control voltage.

For ease of operation, the feedback loop and other components needed to convert a variable gain amplifier into a voltage controlled network may be assembled as a separate module, to be "plugged in" to a variable gain amplifier module. The signal input and output would then be connected to the "network" module, while the control current would be applied to the amplifier module. If the appropriate buffer circuitry were incorporated in the "network" module, then the electronic music composer would have only to insert the desired "filters" in the signal path, and connect the controlling voltages to the appropriate amplifier modules, without concerning himself with the details of the network's functions.

CONTROL TRANSDUCERS

The problem of finding the transducers to enable the musician to most efficiently convert the movement of his hands to control voltages is a study in itself which we began when the design of the above-mentioned modules was completed. I will list the transducers that we have found to be useful, and briefly describe their operation.

First is the standard keyboard. Its utility arises from the fact that most musicians are already adept at its use, and that it permits the accurate selection of a large number of discrete control voltages. The keyboard operates standard leaf switches which select resistors in a resistive voltage divider. The entire divider is supplied from a constant voltage, and the divider output is the control voltage.

A wirewound resistance element, wound on a long straight mandrel, is also used as part of a voltage divider. A thin gold-plated beryllium-copper band, stretched over the mandrel, is depressed at the appropriate spot on the resistance element to make contact. A resistance element with an exponential resistance taper is extremely useful. By winding the resistance element so that the total resistance doubles every 6-1/2" and applying the control voltage to the variable frequency oscillator, then the frequency intervals on the mandrel will be spaced the same as those on a conventional keyboard. The variable resistance element may either be "played" like a keyboard or varied continuously to produce glissandos, vibratos, etc.

Hand-capacitance sensors can be made in a wide variety of configurations. A simple, R.F.-excited circuit such as is used in contemporary theremins, is applicable here.[9] The theremin volume antenna circuitry produces useful voltage changes when a person's hand is brought within 8 inches of a 15 square inch metal plate. The same circuitry can be used in conjunction with a capacitor made up of two small, closely-spaced metal plates, one of which is mounted on a stiff leaf spring. The force of a person's hand on the spring will change the capacitance and produce a corresponding control signal. If the control signal is amplified, differentiated, and then used to control a variable gain amplifier, the amplifier gain will be proportional to the velocity of the musician's hand as he strikes the control element.

Up to now, the control transducers have been applied to simulate conventional musical instruments. Thus, keyboards and linear variable resistors control pitch, force-sensitive capacitors determine loudness, position-sensing plates vary filtering parameters, and velocity sensors produce percussive amplitude envelopes. Musicians are thoroughly schooled in the use of conventional instruments and it is natural for them to use control transducers with analogous modes of operation. From the electronic musical instrument designer's viewpoint, this approach will bear little fruit, and it would be more worthwhile to investigate, in an objective and systematic way, what transducer configurations will most effectively translate the musician's intent into sound, assuming that a musician "practices" the use of the transducers as earnestly as musicians are now required to practice on conventional instruments.

CONCLUSION

A group of basic audio signal generating, amplifying, and filtering modules has been described. The salient variable of each module is proportional to a control voltage over a range wide enough to insure utility in the production of electronic music. Specialized modules, such as noise generators and ring idge modulators, can obviously be used with the basic modules. veral control transducers, patterned after the control mechanisms of conventional musical instruments, have been used for the sake of expediency.

The simple and predictable relation between the applied control voltage and the salient variable of each of these modules suggests their application in fields other than electronic music production. In particular, the setting up of prototype experimental electronic musical instruments, and the remote-control processing of conventional audio signals are ideal applications for the voltage-controlled modules.

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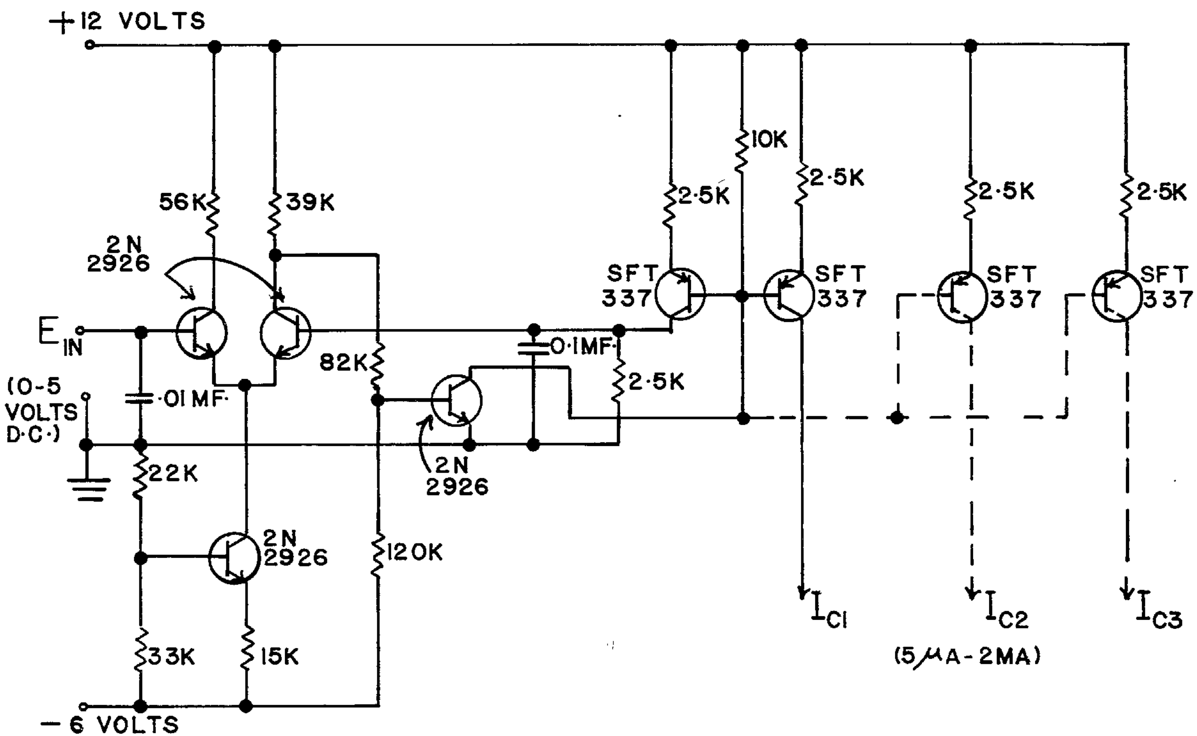


FIGURE 1: Direct-coupled amplifier with multiple current outputs.

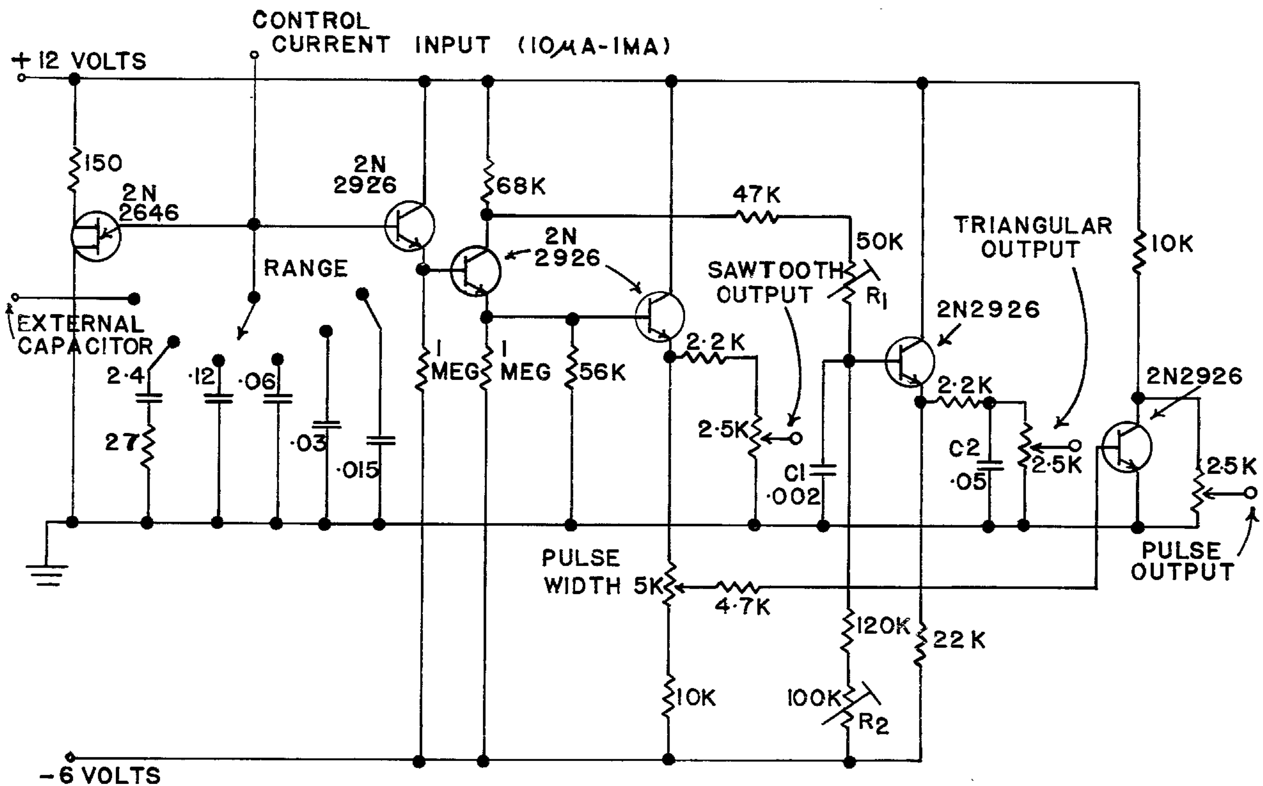


FIGURE 2: Current-controlled relaxation oscillator with sawtooth, triangular, and variable-width pulse output waveforms.

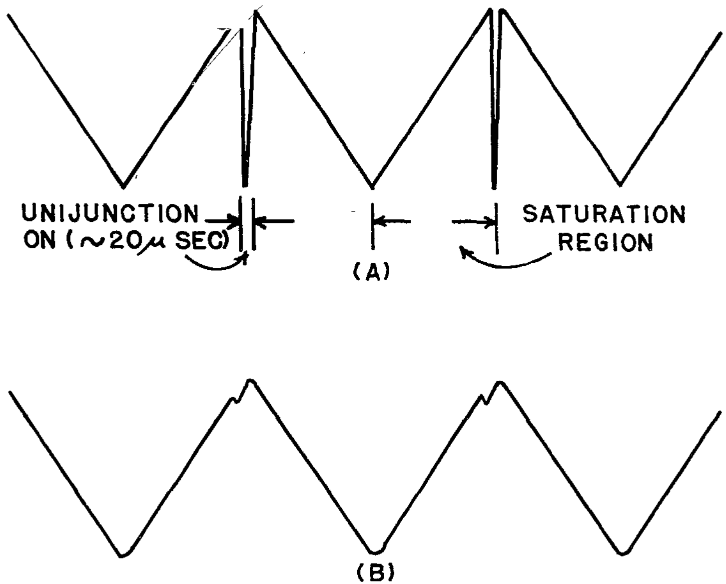


FIGURE 3: (A) Triangular waveform at collector of first wave shaper transistor and (B) after smoothing by C1 and C2.

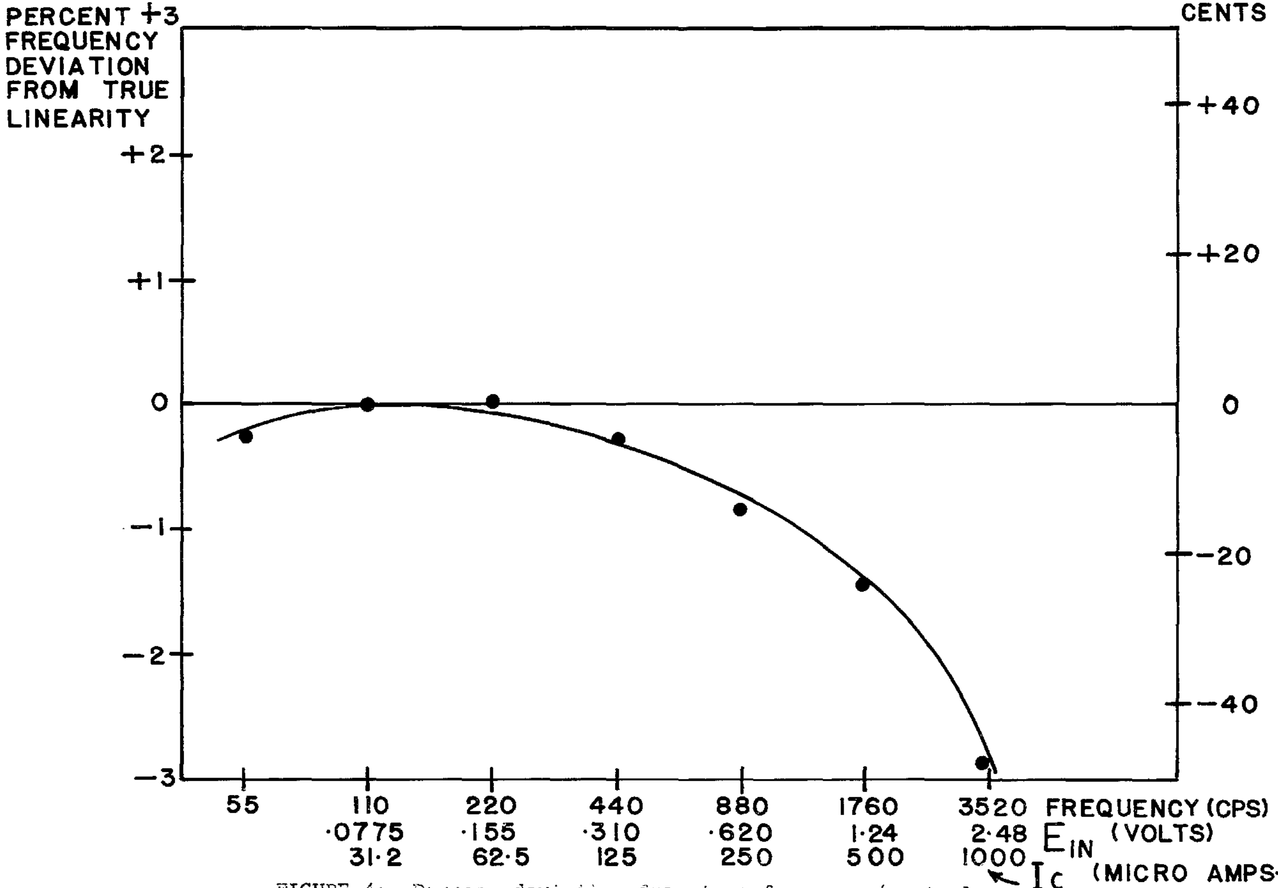


FIGURE 4: Percent deviation from true frequency/control voltage linearity versus frequency, of the variable frequency relaxation oscillator and direct-coupled amplifier combination. Charging capacitor equals .03 MF.

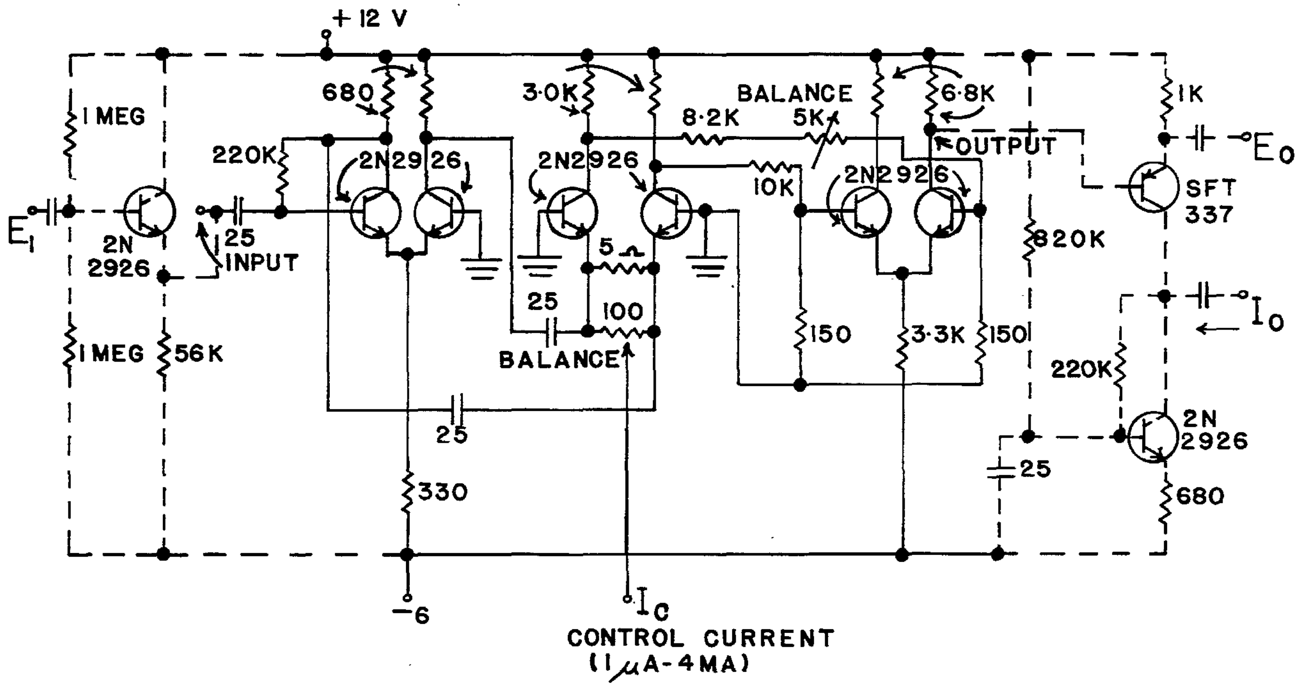


FIGURE 5: Variable gain amplifier. Solid-lined circuit is the basic amplifier and dash-lined portions are buffer stages.

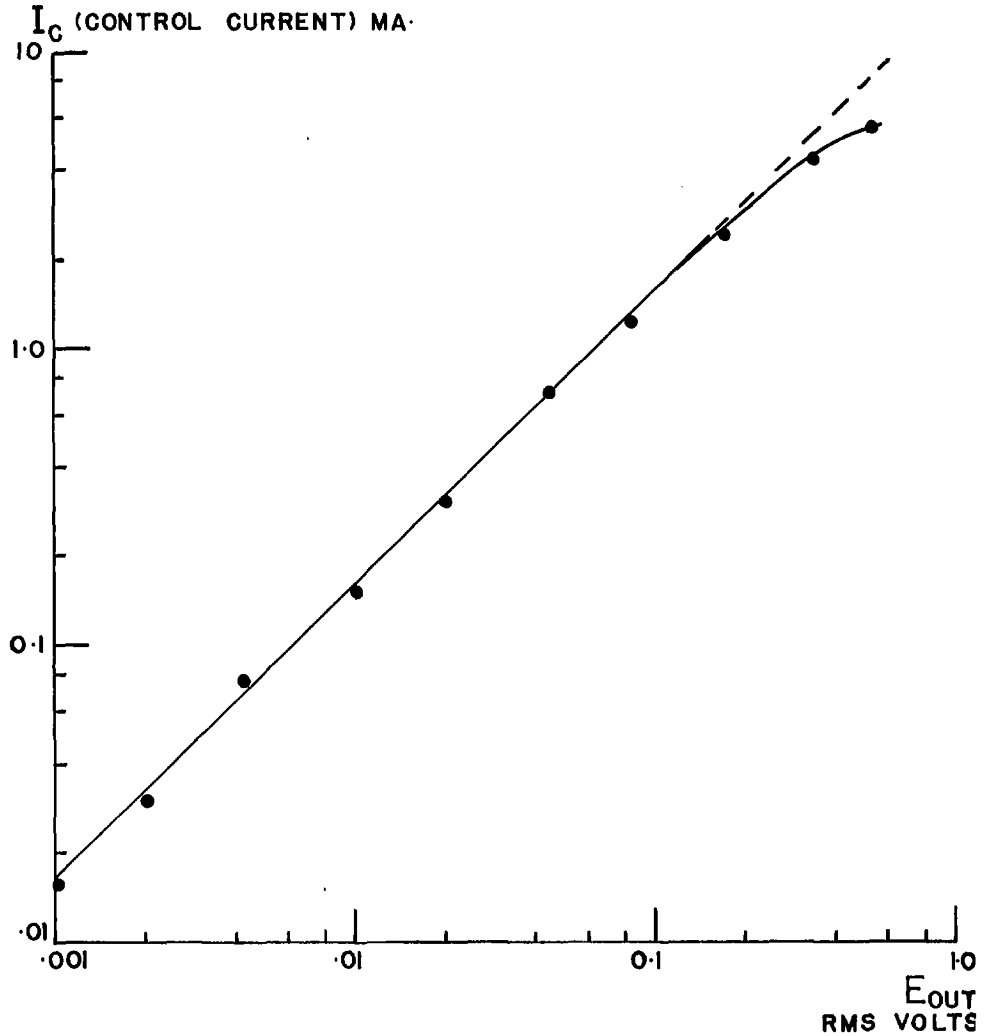
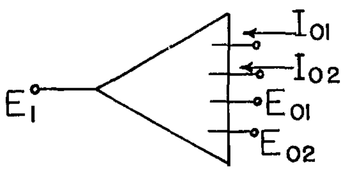


FIGURE 6: Output voltage versus control current of the variable gain amplifier. E_{in} = 5 mv.

DEFINITIONS AND APPROXIMATIONS

DEFINITIONS:



$$I_{01} = I_{02}$$

$$G \equiv \frac{I_{01}}{E_1}$$

$$E_{01} = E_{02}$$

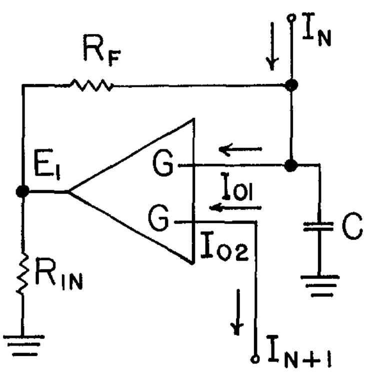
$$K \equiv \frac{E_{01}}{E_1}$$

APPROXIMATIONS

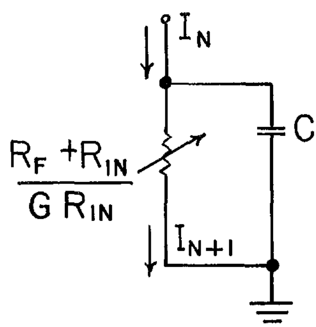
1. Input impedance of amplifier is high enough to be ignored.
2. Admittance of current output is low compared to admittance of external load.
3. Current through feedback resistor is small to total output current.

FIGURE 7a: Definitions and approximations for the expressions in figures 7b,7c, and 7d.

LOW PASS FILTER SECTION



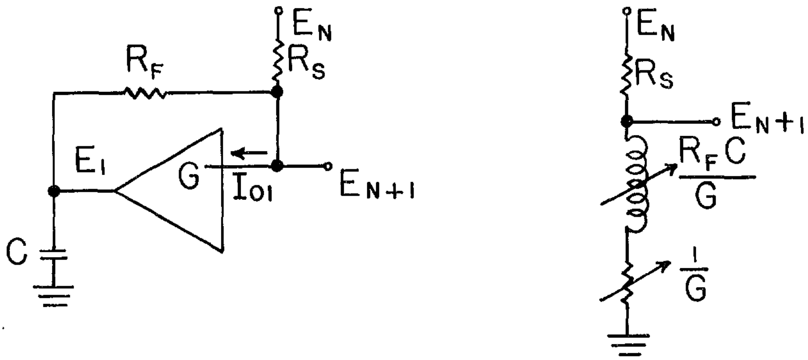
ARRANGEMENT WITH
VARIABLE GAIN AMPLIFIER



EQUIVALENT
CIRCUIT

FIGURE 7b

HIGH PASS FILTER SECTION

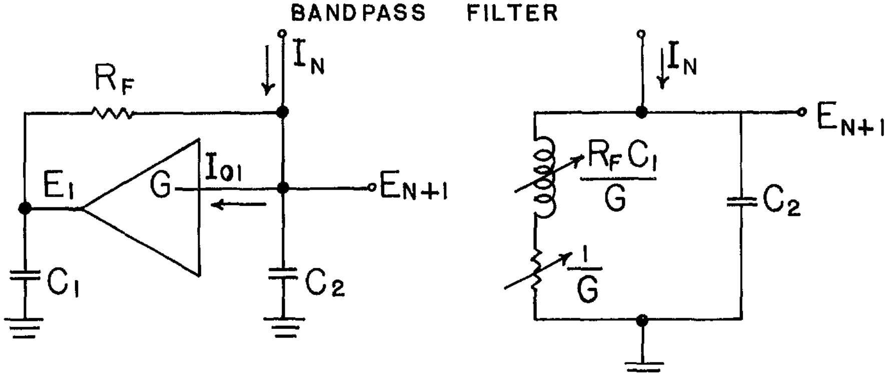


ARRANGEMENT WITH
VARIABLE GAIN AMPLIFIER

EQUIVALENT
CIRCUIT

FIGURE 7c

BANDPASS FILTER



ARRANGEMENT WITH
VARIABLE GAIN AMPLIFIER

EQUIVALENT
CIRCUIT

FIGURE 7d