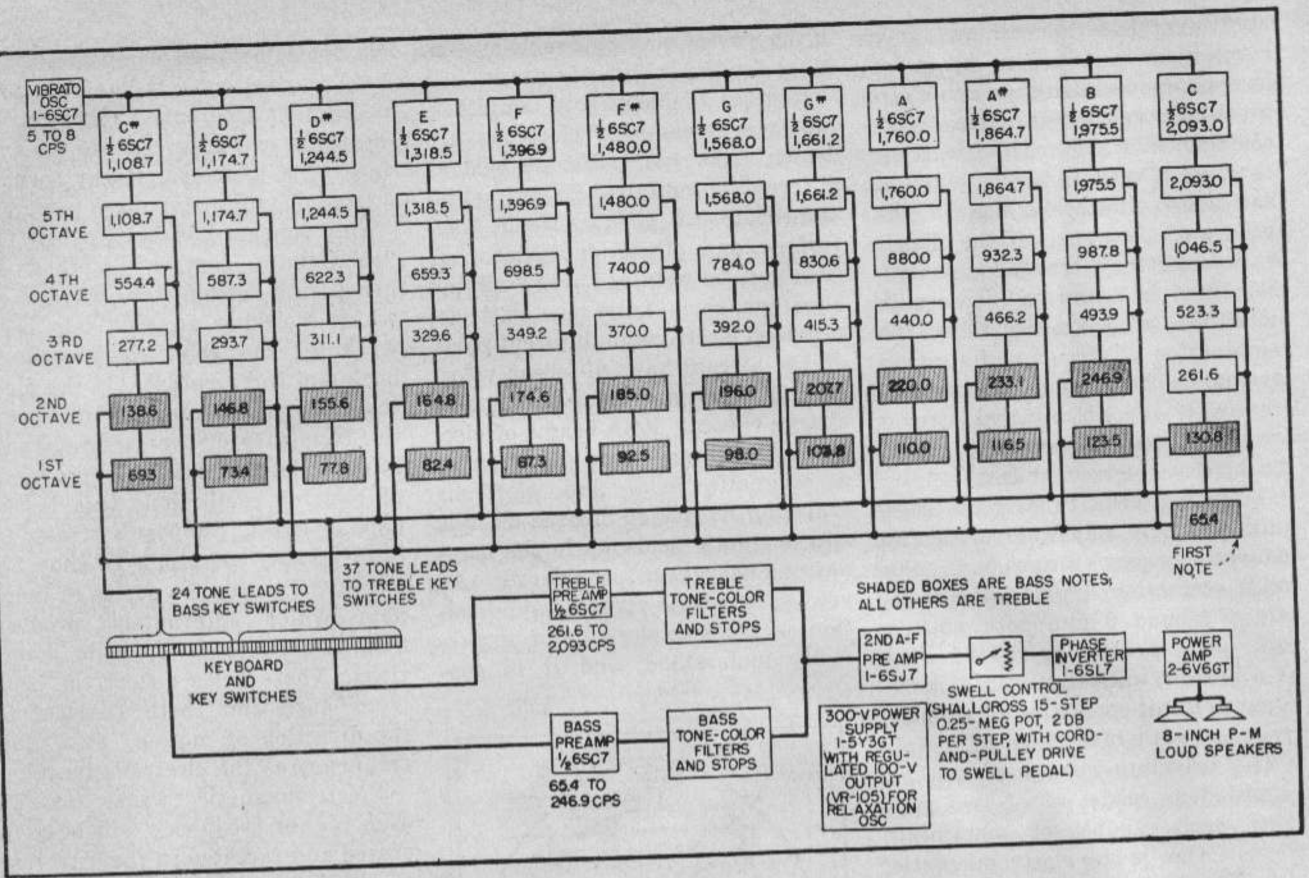


GAS-DIODE ELECTRONIC

Chains of sawtooth tone generators using 10-cent neon lamps are synchronized to master oscillators for frequency control. Undesired harmonics are removed with tone filters to give five octaves of organ-like music with two vibrato stops and six tone-color stops

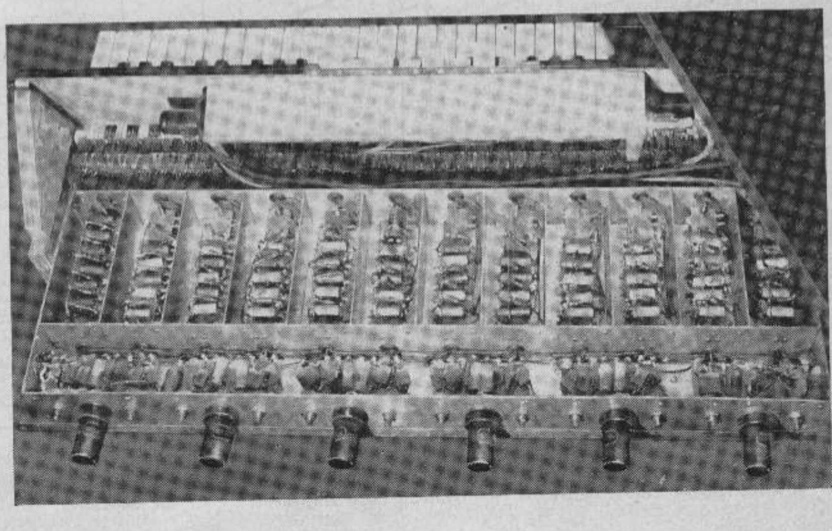
Electric-keyboard musical instruments may be classified into two main groups according to their means of tone production: (1) electromechanical generators; (2) electric-circuit generators. Mechanical systems are either rotary or vibratory. Both means have been used to modulate electrostatic or magnetic fields or beams of light. Electric circuit types have employed both vacuum and gas-tube oscillators as tone generators.

Designers of new instruments have either imitated existing instruments or have devised completely new pleasing tonal qualities and controls. However, one of the greatest complaints against electric instruments is that they are generally too perfect, and therefore unnatural. Variation is the essence of musical expression and variations in pitch, loudness, tone color and vibrato should be within easy control of the musician. On the other hand, too many controls confuse or discourage the performer. In general, new instruments should be easily operated by masters of similar existing instruments.

It was required to develop an organ-like electronic instrument that would retail for $800, whereas the cheapest all-electronic organ then available sold for about $3,000. Since mechanical economies in the design and construction of the console and keyboard would classify the equipment as a toy rather than a musical instrument, it was necessary to retain the standard form of the other low-priced organ-like instruments. The main savings were effected in parts and production costs, with minimum sacrifice in performance. A standard organ keyboard of five octaves or 61 notes covering the range from C 65 to C 2,093 cycles is used. The controls consist of eight organ stops; two are used to select vibrato rates and the remaining six are for tone color. A swell pedal is provided for output level or volume control.

The cheapest double-triode vac-

FIG. 1—Arrangement of stages in complete organ. Frequency value in cycles is given for each master oscillator (top row) and each of the 61 synchronized NE-2 neon-tube relaxation oscillators comprising the five octaves. Shaded boxes represent bass notes



TOP: Complete organ being played; CENTER: Rear view of console, showing general arrangement of electronic units; BOTTOM: View of chassis containing the twelve master oscillators and twelve octave chains. Total tube complement is eight 6SC7, one 6SJ7, one 6SL7, two 6V6GT, one 5Y3GT, one VR105 and 61 NE-2 neon diodes

ORGAN

By ROBERT M. STRASSNER
Monterey Park, Calif.

uum tube, the 6SC7, lists for $2.00. The cheapest gas diode, the NE-2, lists for 10¢. For this reason, gas-tube methods of tone generation were thoroughly investigated. As it happens, the sawtooth waveform of the gas-discharge relaxation oscillator has a high harmonic content, permitting wide variation in tone color by removing the undesired harmonics with suitable filters. The main difficulty was, of course, with frequency stability.

Actual Design

The block diagram of the complete instrument is shown in Fig. 1. The twelve separately-tuned master oscillators generate continuously the twelve frequencies for the highest of the five octaves provided. For each master oscillator there is a chain of sawtooth tone generators, the first of which is synchronized to the fundamental frequency. Only these harmonic-rich sawtooth generators feed the preamplifiers and tone-color filters; the master oscillators serve only for frequency control and are not heard.

Each master oscillator synchronizes its corresponding submultiple notes in cascade fashion. Of course, octave submultiples are the only frequencies that may be synchronized in a musical instrument, since the others are not exactly related in the equally-tempered scale.

The 61 sawtooth tone generators are continuously in operation, with all their output leads terminating at the keyboard switches. Twenty-four of the generators feed the bass preamp, and the remaining 37 feed the treble preamp. When the musician depresses one or more keys, the corresponding key switches send the tonal combination to the treble and/or the bass preamp. Stops at the control panel select the desired combination of tone color. The bass and treble tone-color filters then separately modify the upper and lower portions of the keyboard and inject their combined outputs at the second preamp grid. The input level to the phase inverter is controlled by a step potentiometer operated by the foot of the performer. The signal continues through the power amplifier to the dual-speaker combination.

The main factors affecting the frequency stability of gas-discharge oscillators were found to be applied voltage and incident light. Voltage was readily stabilized within 2 percent with a VR105 regulator tube. It was necessary to introduce a small amount of light for proper operation at the lower frequencies. This effect was accomplished by placing ordinary six-volt dial lights near the low-frequency gas diodes.

The necessary additional stabilization was obtained by subjecting the tubes to a small electrostatic field at the controlling frequency. By using a portion of the output from one oscillator whose frequency was already under control to synchronize another at a submultiple frequency, octave divider chains were developed. Three or four turns of hookup wire provided sufficient coupling for reliable control within plus or minus 10 percent of the free-running frequency.

Figure 2 shows a typical octave-divider chain. The charging capacitors for the first three stages are connected so that the output voltage to the treble preamplifier approaches −100 volts according to the relation:

$$V = 100\,(1 - e^{-t/RC}) \qquad (1)$$

The time for discharge is extremely short compared with the time required for the voltage to increase from the extinction voltage V_e to the ignition voltage V_i, so that the free-running frequency of oscillation is mainly a function of the difference between these two voltages[1]. Substituting V_e and then V_i for V and taking the reciprocal of the difference between the two corresponding values of t, the frequency of oscillation becomes

$$f_o = \frac{1}{RC \ln\left(\dfrac{100 - V_e}{100 - V_i}\right)} \qquad (2)$$

This expression is approximate because V_e and V_i are themselves affected by frequency, incident light, temperature and magnitude of the discharge current.

At the point of ignition, in the first three stages, the output voltage rises very quickly to +100 volts. The last two tubes in the chain, V_4 and V_5, are connected so that a positive-approaching sawtooth is produced. It was found that the steep time rise at the point of discharge in the negative sawtooth is much more effective in controlling the positive-sawtooth generators than other combinations. Because the lowest frequencies are the more difficult to control, the last two tubes in the chain are both controlled by the steep negative sawtooth. The first three tubes in the chain, V_1, V_2 and V_3, are controlled directly by the master oscillator.

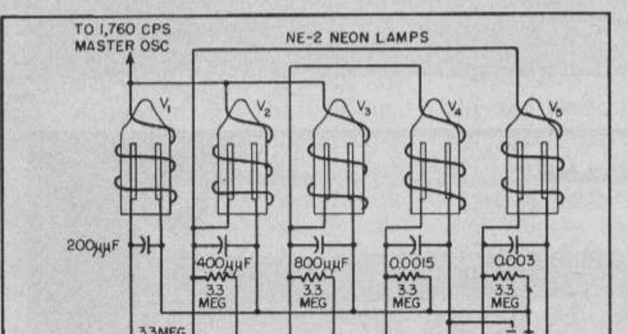


FIG. 2—Example of octave divider chain. For 6-note C chain, sync signals are injected in slightly different order so that the two lowest notes (most difficult to control) are triggered

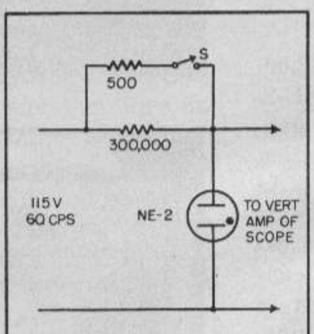


FIG. 3—Neon-lamp test and aging circuit for improving stability of sawtooth oscillators

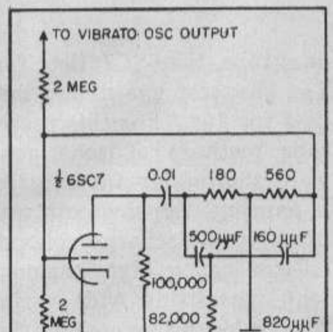


FIG. 4—Typical master oscillator circuit, with component values for the 1,760-cps chain

The charging resistance was adjusted to about 3.3 megohms in all cases. This value represents a compromise between higher values, which would be more unstable against temperature variations and would limit the discharge current, and lower values that operate the tube too near the border between oscillation and continuous glow. For all other factors remaining constant, Eq. 2 shows that if R is increased, C must necessarily be reduced if frequency is to remain constant. A reduction in C means less energy storage in the capacitor and therefore less discharge current. If R is too low, the charging current will be so high that the tube is unable to extinguish at the completion of capacitor discharge, which results in continuous glow.

Switches S_1 through S_5 are mechanically linked to the playing keys. When in the up position, these switches ground the outputs of all unplayed oscillators and also parallel the 15-meg resistors from grid to ground of the preamps, giving 0.625 meg and 0.405 meg respectively at the bass and treble inputs. As a key is depressed and the ground connection removed, a 28-db loss of available oscillator output for bass notes and 31-db loss for the treble is momentarily sent to the preamps. When the key has completed $\frac{3}{8}$ of its stroke, the 15-meg resistor is shunted, thereby allowing playing level. In this manner the loud transient click that would otherwise be present has been almost completely eliminated.

Despite these precautions against transients, key switches with silver alloy contacts caused considerable clicking. Evidently these high-impedance circuits were extremely sensitive to the slightest oxide coating at the contacts. Even the best silver forms a slight coating under normal conditions. The final switches were formed from Nichrome V wire. Clicking was unnoticeable and these switches have maintained their characteristics for a long period of time.

After the first experimental model had been in use for several months, a few oscillators drifted out of their range of control. It was determined that an aging process within the tubes had taken place. It was observed that the glow in troublesome tubes was irregular and unevenly spread over the electrode area. When these tubes were tested as positive and negative peak clippers in the circuit of Fig. 3 (switch S open), they failed to produce square and symmetrically clipped sine waves. When the switch was closed for several seconds, allowing about 200 ma to flow, the glow started unevenly but gradually spread over the entire area of both electrodes. At the completion of this spread, the switch was opened because continued application of this high current overheats the electrodes and destroys their photosensitive coating. After proper aging, the wave is always symmetrical and squarely clipped. Uniform characteristics throughout the remainder of their life were thereby assured. The experimental model has remained in synchronism for well over a year.

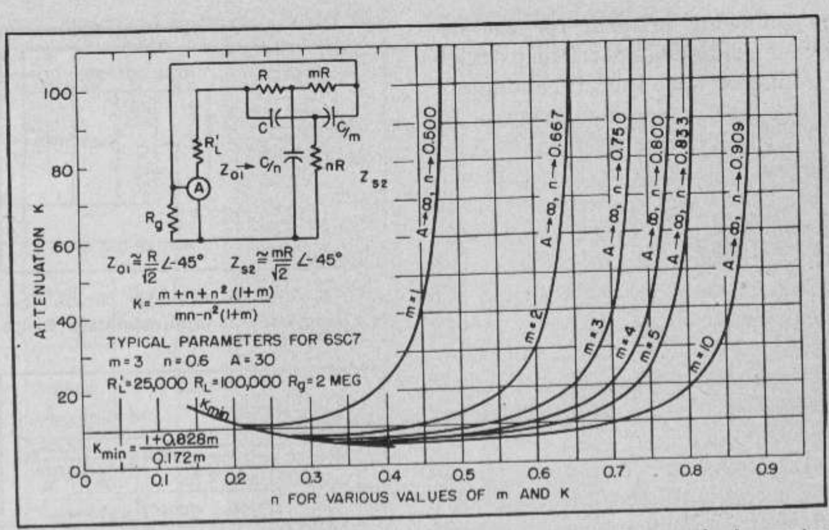


FIG. 5—Design curves for determining parameters of parallel-T networks in master oscillators

Master Oscillators

At the frequencies corresponding to the twelve notes in the highest octave, twelve stable oscillators were used to control eleven chains of five notes and one of six to account for the extra C at the low end. Because of its high stability and low parts cost, the parallel-T circuit was chosen. Stabilities of 0.1 percent are possible without supply-voltage regulation. Since only one triode per oscillator is required, two master oscillators may be housed in one double triode tube. Typical circuit constants of the A-chain master oscillator are shown in Fig. 4.

To aid in determining the parallel-T network parameters, the curves for Fig. 5 were plotted from equations already derived[2]. This presentation assumes zero generator impedance and infinite load impedance. Therefore, the network open-circuit input impedance Z_{o1} should be much greater than the generator impedance R_L' and its short-circuit output impedance Z_{s2} should be much less than the load impedance R_g in order that the network balance conditions be least disturbed. After stage gain A has been determined by the tube and load resistor selected, n as a function of A for various values of m may be read directly from the curves.

For sustained oscillation, network attenuation K must be less than stage gain A. If there is no loading on the network and constants are to exact tolerance, K could be taken equal to A. This is, of course, impossible and for reliable operation, K should not be more than one-half A. In most of the literature on the subject, m is taken equal to one.[3,4] It should be noted that increased selectivity as well as decreased K occurs as m is increased.

The more common method of increasing selectivity is to increase A only. With high-mu triodes the upper limit on A is about 35, so that if additional selectivity is desired, increasing m is a convenient method. With these limits in mind the following criteria for the design of a single-stage triode parallel-T oscillator were therefore adopted: (1) A was determined from μ, R_L and r_p; (2) K was set equal to $A/2$; (3) the highest value of m that will allow Z_{o2} to remain much less than R_g was selected; (4) Z_{o1} was made much greater than R_L'; (5) at the chosen value of m, n was found for K calculated above; (6) only points well above the K_{min} curve and below where K changes rapidly with small changes in n were used; (7) $C = 1/\omega R$.

Although the design was time-consuming and the required low-tolerance components are expensive, the production cost per oscillator is less than for other types and stability is comparable with a laboratory standard.

Vibrato Oscillator

Vibrato in most musical instruments is produced by combined frequency and amplitude modulation. However, a rather pleasing effect may be obtained from frequency modulation alone. Figure 6 shows the vibrato oscillator, which is a standard four-section phase-shift variety.[5] Frequency is adjusted to about six cycles per second and is controllable at the stop tabs by simultaneously varying two of the 1-meg resistors in the phase-shift network. Oscillator output is injected through the 2-meg resistors shown in Fig. 4 to the grids of all master oscillators. The extent of the frequency swing or vibrato depth is determined by the amplitude of the injected voltage.

Tone-Color Stops

The raw sawtooth waveform from the tone generators could hardly pass for music because of its improper harmonic distribution. After this sawtooth has passed through filter circuits that alter its harmonic structure, many pleasing tonal effects are obtained.

The highest note on the keyboard of this instrument is the 32nd harmonic of the lowest. A low-pass filter designed to remove certain harmonics of the treble notes would have negligible effect on bass notes. In like manner, another low-pass filter with a much lower cutoff point would be very effective in coloring bass notes and yet completely attenuate the treble section. If uniform tone color were required, a separate filter for each tone color of each note would be needed. However, few instruments have the same tone color throughout their range.[6,7] A satisfactory tonal balance was obtained by splitting the keyboard at middle C (261 cycles). Two filter sections were provided. The 24 notes below middle C were routed to bass stops or filters and the 37 above to treble stops. When a bass note is played and a bass stop is closed, a tone is produced that in pitch is determined by the note played, in color is designated by the stop closed and is at a level depending on the setting of the swell pedal. Figure 7 shows circuit constants of the tone color unit. One filter in each section is a resonant band-pass type designed to act as a formant-producing element. (Formants are caused by boosting partial tones around a particular resonance frequency.) The others are ordinary R-C networks. These combinations produce horn, string and reed effects. Large amounts of insertion loss were deliberately incorporated in each network in order that output level would be noticeably increased as more stops were closed.

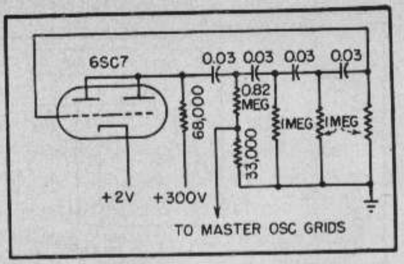


FIG. 6—Vibrato oscillator circuit. Output frequency is approximately 6 cps

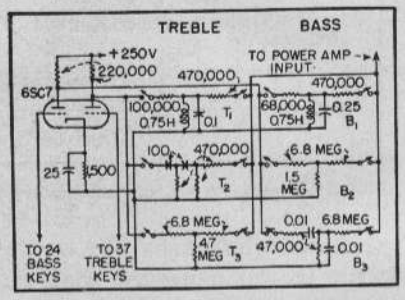


FIG. 7—Bass and treble tone-color filters, each using half of the 6SC7

Choice of Speakers

The distortion of the 8-watt amplifier used was held to a minimum consistent with parts cost, but best speaker performance (oddly enough) was realized with one of the least expensive combinations tested. The final choice was a pair of 8-inch p-m speakers, one with a hard cone resonating at 150 cycles and the other soft for a 75-cycle resonance. When these were operated in parallel, their reciprocal damping effects appeared to reduce overall resonance and distortion to a low degree. An 8-watt test signal that produced objectionable distortion in a 25-watt high-fidelity speaker supplied by a prominent manufacturer was easily handled by the 10-watt combination used. The dual system was also chosen because it allowed a more uniform dispersion than could be realized from even a large single speaker.

Conclusions

It was pointed out that the purpose of this project was to design a low-cost, easily-operated organ-like instrument. Low manufacturing cost was accomplished by using inexpensive tone generators whose tiny size lend themselves to small identical subassemblies. Pleasing tone color was the main standard of performance. To this end, comments on the results of listening tests by many musicians and engineers have been most gratifying. Provided reasonable care is exercised in the selection of capacitors and resistors in the parallel-T networks, the instrument should remain in tune indefinitely. Eight organ stops provide 196 combinations of tone color. Any person able to play keyboard instruments can play this instrument with little or no practice.

REFERENCES

(1) H. J. Reich, "Theory and Application of Electron Tubes," p 454, McGraw-Hill Book Co., New York, 1944.
(2) H. S. McGaughan, Variation of an RC Parallel-T Null Network, *Tele-Tech*, p 48, August 1947.
(3) W. G. Shepherd and R. O. Wise, Variable Frequency Bridge-Type Frequency-Stabilized Oscillators, *Proc. IRE*, p 256, June 1943.
(4) A. E. Hastings, Analysis of a Resistance Capacitance Parallel-T Network and Applications, *Proc. I.R.E.*, p 126, March 1946.
(5) L. Stanton, Theory and Application of Parallel-T Resistance Capacitance Frequency Selective Networks, *Proc. I.R.E.*, p 447, July 1946.
(6) S. K. Lewer, "Electronic Musical Instruments," *Electronic Engineering*, 1948. This monograph has an extensive bibliography and lists American and British patents.
(7) B. F. Miessner, Electronic Music and Instruments, *Proc. IRE*, p 1,427, Nov. 1936.