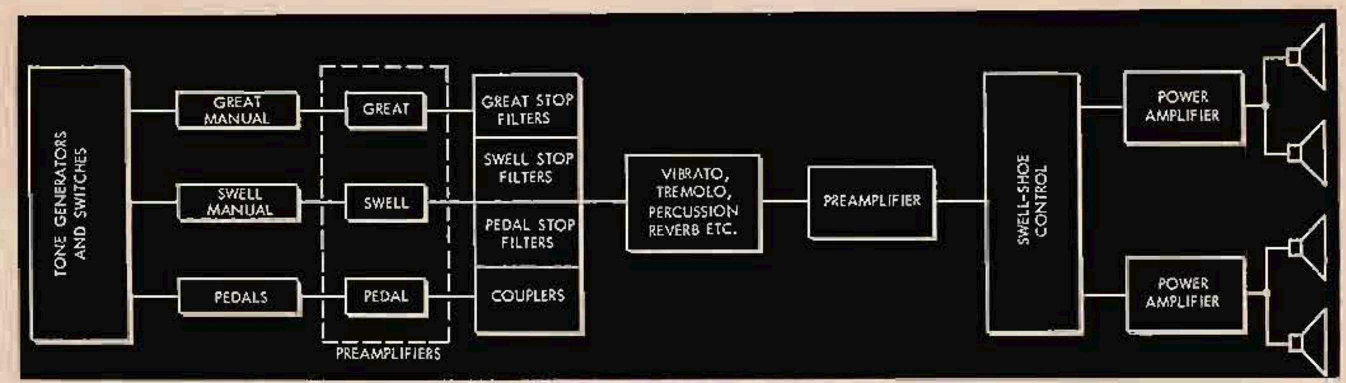

Fig. 1. Block diagram for electronic organs.

Electronic Organ Tone Generators

D. WOLKOV*

Electronic organs produce musical tones by means of electro-mechanical or electronic oscillators, with the electronic type being used in the majority of existing organs.

In Two Parts—Part I

WHAT IS A MUSICAL INSTRUMENT? Is an electronic organ a musical instrument? There are purists who insist that there is only one organ which is a musical instrument—the air organ. Certainly, the electronic organ family which starts with $39 toys and ends at $50,000 systems has many members which are not musical instruments.

A musical instrument must be capable of producing all of the responses needed by the musician—legato, staccato, percussive attacks, changes in tone, subtle nuances. In addition, in an organ, the musician demands the capability of changing the voice of his instrument, much more than muting a violin or a trumpet. Complete discussions on the psychology of music are contained in references 1, 2, and 3.

Before proceeding to an understanding of the mechanisms and techniques used in the production of electronic musical tones, we need to recall that musical sounds are usually complex waves (was this not the reason for the advent of the high-fidelity art?) as opposed to the sine-wave simplicity of a code oscillator. Incidentally, sine waves are monotonic, square waves contain odd harmonics, triangular (or sawtooth) waves contain all harmonics, and complex waves contain a peculiar pattern of harmonics.

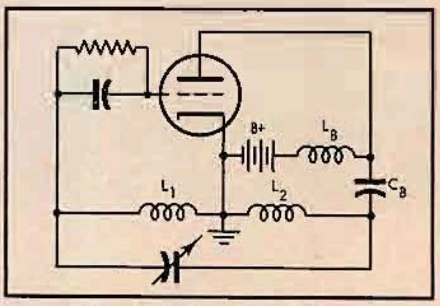

Fig. 2. Hartley oscillator.

Every musical note has a definite fundamental pitch (frequency) and "tone quality" or "timbre" which depends upon wave shape. A musical note not only includes a fundamental frequency (usually less than 6000 cps in an organ) but also one or more "harmonics" or "overtones." These harmonics are an integral multiple of the fundamental frequency. The ear does not distinguish the harmonics independently, but instead identifies the note as a complex tone having the pitch of the lowest component or fundamental. The complete frequencies for nine octaves corresponding to open air pipes ranging from ⅛ foot to 32 feet is given in Table I.

Musical notes in our western culture

OPEN PIPE LENGTH	32'	16'	8'	4'	2'	1'	1/2'	1/4'	1/8'
NOTE:									
C	16.35	32.70	65.4	130.81	261.62	523.25	1046.50	2093.00	4186.00
C#	17.32	34.64	69.29	138.59	277.18	554.36	1108.73	2217.46	4434.92
D	18.35	36.70	73.41	146.83	293.66	587.33	1174.65	2349.31	4698.63
D#	19.44	38.89	77.87	155.56	311.12	622.25	1244.50	2489.01	4978.03
E	20.60	41.20	82.40	164.81	329.62	659.25	1318.51	2637.02	5274.04
F	21.82	43.65	87.30	174.61	349.22	698.45	1396.91	2793.82	5587.65
F#	23.12	46.24	92.50	184.99	369.99	739.98	1474.97	2959.95	5919.91
G	24.50	49.00	98.00	195.99	391.99	783.99	1567.98	3135.96	6271.92
G#	25.95	51.91	103.82	207.65	415.30	830.60	1661.21	3322.43	6644.87
A	27.50	55.00	110.00	220.00	440.00	880.00	1760.00	3520.00	7040.00
A#	29.13	58.27	116.54	233.08	466.16	932.32	1864.65	3729.31	7458.62
B	30.86	61.73	123.47	246.94	493.88	987.76	1975.53	3951.06	7902.13
OCTAVE NUMBER	00	0	1	2	3	4	5	6	7

TABLE 1. Frequencies of 9 octaves in the equal tempered scale.

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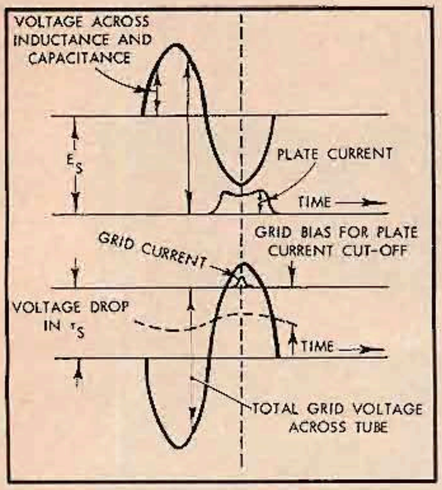

Fig. 3. Time-current-voltage relationships in a vacuum tube oscillator.

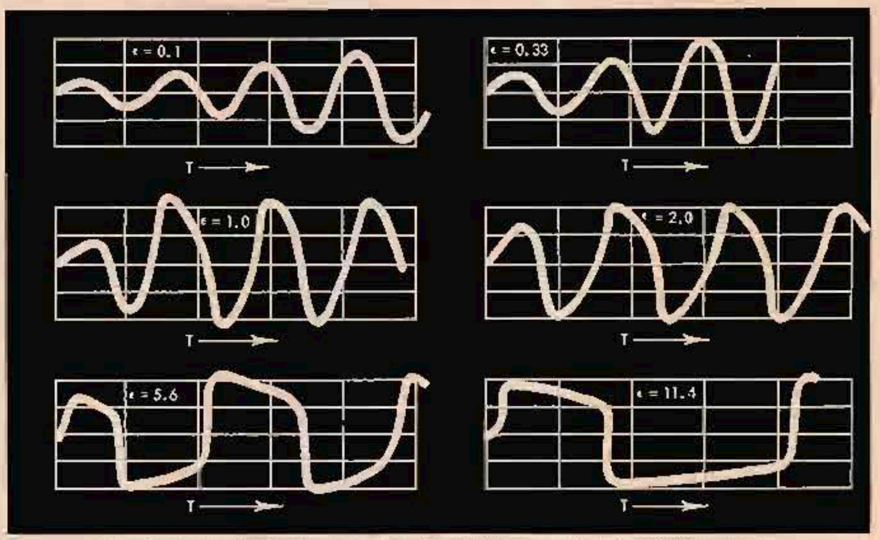

Fig. 4. Typical solutions to van der Pol's equation for different ε's.

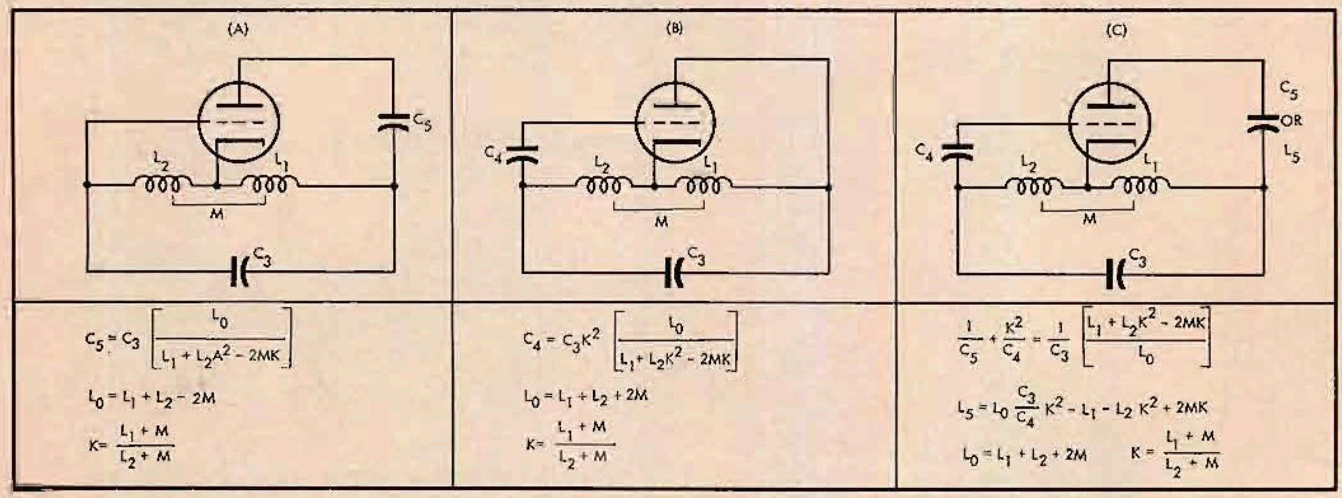

Fig. 5. Stabilization of Hartley oscillators: (A) plate stabilized; (B) grid stabilized; (C) plate and grid stabilized.

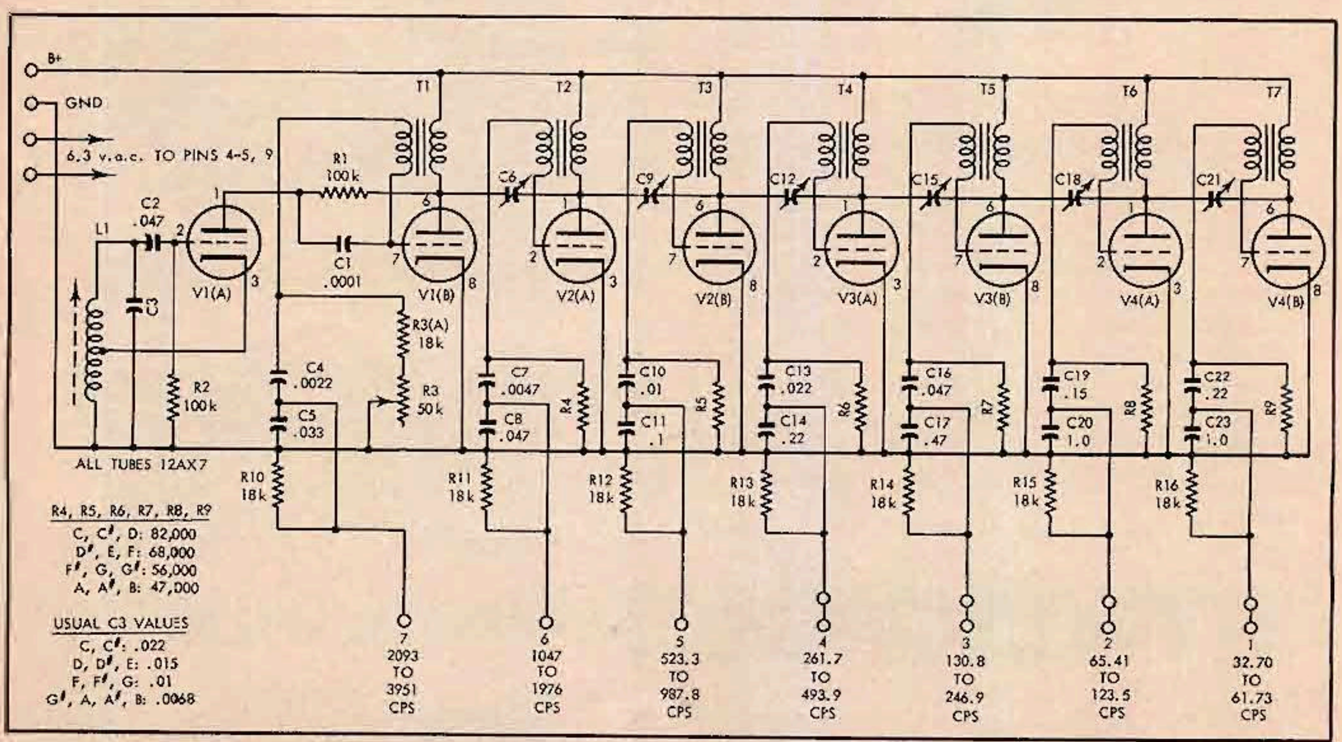

Fig. 6. Tone generator for Schober Concert Model.

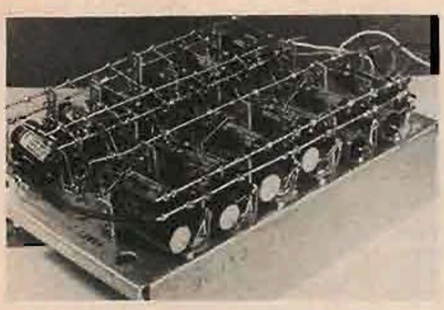

Fig. 7. Conn tone generator chassis.

occur at specific frequencies. The internationally agreed frequency for the note A above middle C is 440 cps. The next A up is 880 cps and the next A down is 220 cps. All of the intermediate twelve tones in an octave are approximately $\sqrt[12]{2}$ apart in frequency.

The $\sqrt[12]{2}$ relationship is a characteristic of the equally tempered scale used on all keyboard instruments. Such a scale involves a compromise. The musical fourth and fifth intervals are tuned to a frequency ratio slightly different from $\sqrt[12]{2}$. If a musical fifth interval were tuned to an exact frequency ratio such as 1.5 to 1, there would be no beat. However, the tempered scale ratio is 1.498 to 1. The second harmonic of one note and the third harmonic of the other are not exactly alike but are close enough to produce an audible beat since their frequency ratio is 2.996 to 3.

Figure 1 is a block diagram for an idealized electronic organ. In practice, some of the functions are performed in blocks different from those shown. In describing the designs of various organs, we will frequently be in more than one block at a time. We will discuss tone generators first and then proceed with tone modifying devices later. Recognize, of course, that in many fine organs no such artificial separations exist.

Musical instruments are *mechanical* oscillators. In contrast, the front end of an electronic organ is an *electronic* oscillator. Basically, there are two types of tone generators: the first type attempts to reproduce air organ sounds, and the second type simulates them electronically. The latter type we can break into two sub-groups. In the first sub-group, electronic oscillators generate complex patterns and tone modifying networks provide frequency modifications. In the second sub-group, musical sounds are produced by the electronic "addition" of appropriate sine waves, a process known as "synthesis."

Tone generators can also be classified in terms of their design. Three such groups are important:

1. Vacuum tube or transistor oscillators
2. Electro-mechanical oscillators
3. Neon tube (relaxation) oscillators.

Electronic Oscillators

Vacuum-tube (or transistorized) oscillators form the basis for tone generation for the largest number of organs. A vacuum tube is able to act as an oscillator because of its ability to amplify. The power required by the input of the tube is much less than the output of the tube. Thus, an amplifier can supply its own input. When this is done under certain conditions, oscillations will occur.

In general, voltage feedback from the output is applied to the grid 180 deg. out of phase and of sufficient magnitude to produce continuous oscillation. In the Hartley oscillator (which is the one most prevalent in electronic organ design, *Fig.* 2), the coupling is accomplished by applying to the grid a portion of the voltage developed in the resonant circuit. The frequency at which oscillations occur is the frequency at which the voltage from the plate circuit is of exactly the proper phase and magnitude to supply its own input (see *Fig.* 3).

A mathematical analysis (Reference 4) shows that in order for the voltage on the grid to have exactly the required phase, the frequency of oscillation must

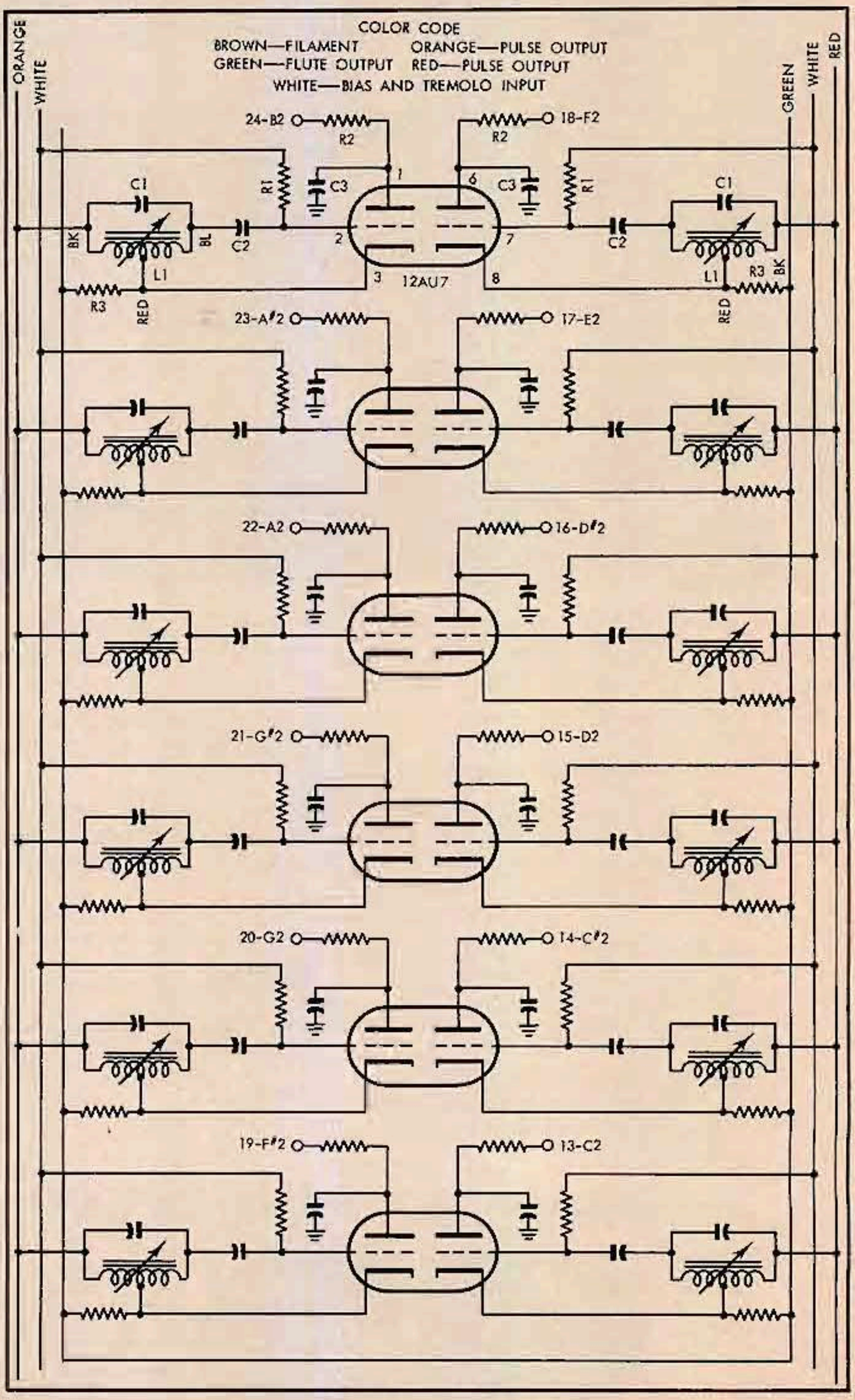

Fig. 8. Conn tone generator schematic.

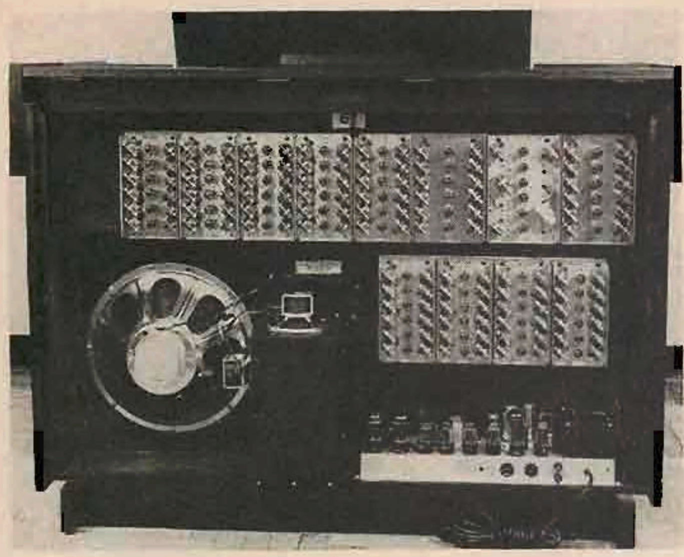

Fig. 9. Rear view of Conn organ showing location of tone generators.

be higher than the resonant circuit frequency. It can be demonstrated that the frequency stability will be highest when the natural oscillations differ as little as possible from the theoretical "*f*" of the tuned circuit.

Although frequency stability is directly proportioned to the Q of the tank circuit, the use of a high Q means loose coupling. Thus, high stability and high power output are mutually incompatible. In practice, the best organ designs are such that no power is taken from the oscillators. As a compromise, some designs draw minimal power.

The complete mathematical solution of even the simplest vacuum tube oscillator is extremely complex. Van der Pol was able to arrive at useful approximations by using such assumptions (Reference 4) as:

a. The grid bias voltage is obtained through external means;

b. That no grid current flows; and

c. The μ of the tube is constant.

See *Fig.* 4 for some graphical solutions.

It is a necessary condition that α, the damping factor of the circuit, be negative. The waveform is dependent on the product, ε, of α and LC. As mentioned earlier, sawtooth, square, and sinusoidal wave forms are useful in electronic organs.

To keep the inductances, capacitances, and resistances (external to the tube) constant in value is a problem in the design and temperature control of those parts. On the other hand, regardless of the design, the effective impedance of the tube itself changes with use and with supply voltages.

However, by adjusting the other circuit parameters, the dependence of the frequency on the tube impedances can be minimized. Through the use of the reactances in the series grid and plate circuits, it is possible to design oscillators which to a first approximation are independent of tube conditions (see *Fig.* 5). In the ideal cases, compensation is perfect and the frequency is independent of tube conditions. In practice, however, the compensating reactances are not perfect and they must be adjusted by trial. This is what is meant by tuning. Further information on the design of stable electronic oscillators is given in References 5, 6 and 7.

A continuously running oscillator, though it simplifies the design of the oscillator, brings on design problems in the keying circuits. Most musical instruments have an envelope in which the sound intensity rises rapidly and then decays gradually. Usually, continuously running organ oscillators have associated with them decay and declicking circuits for each key.

A gated oscillator is one in which plate voltage is applied through the switch closure and the amplitude of oscillation builds up as shown in *Fig.* 4. In the past, designers tackled de-clicking as an easier solution to the problem of keying 300 volts B+ in the plate circuit of the oscillator. Allen Organ and others are now using transistors and are effectively keying the oscillator with 15 volts. The switch design for these low currents is one that takes the designer into the area of dry circuit contacts. Many of the switches used in current organ manufacture are electro-mechanical achievements.

Before inspecting the structure of oscillators used in present organ designs, it should be mentioned that for reasons of economy organ designers will often compromise so that each oscillator may supply more than one tone. This complicates or may even void the possibility of playing the associated notes simultaneously. This is particularly true as a compromise in the design of pedal generators and leads to the one-note-at-a-time pedal playing.

Polyphonic music is pleasing because of minute changes in pitch and timbre. A chorus of human voices all singing the same note sounds richer than one voice. A piano has three strings for most of the notes not only for acoustical power but also to provide a very slow beat frequency. This beating comes about because of the not-quite-exact tuning of the three strings (or two) associated with the note. Air organ builders created a similar effect by paralleling sets of pipes.

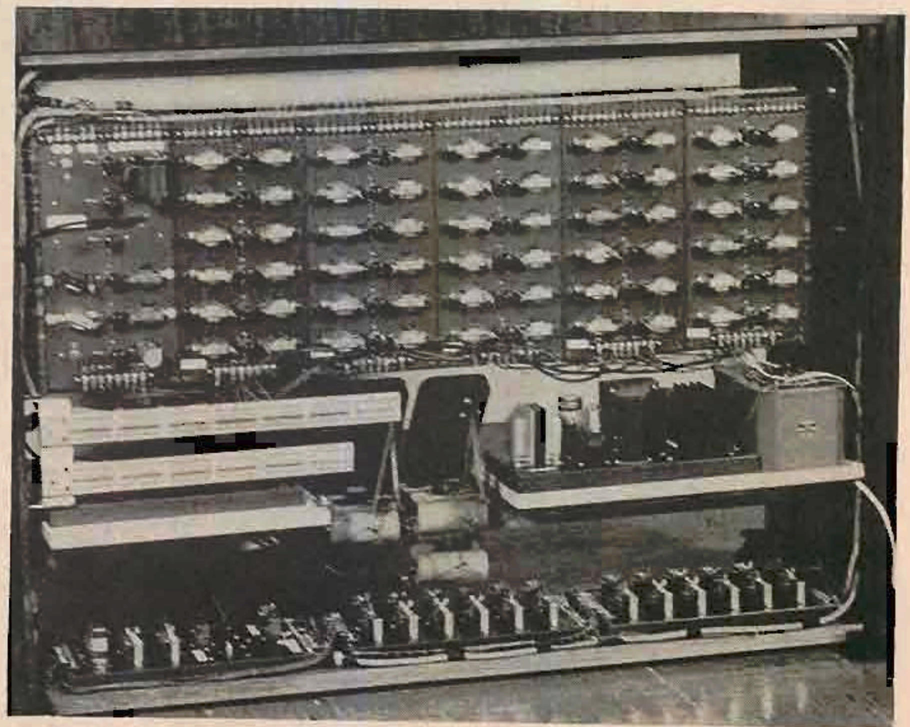

Fig. 10. Rear view of Artisan organ (kit) showing location of tone generators.

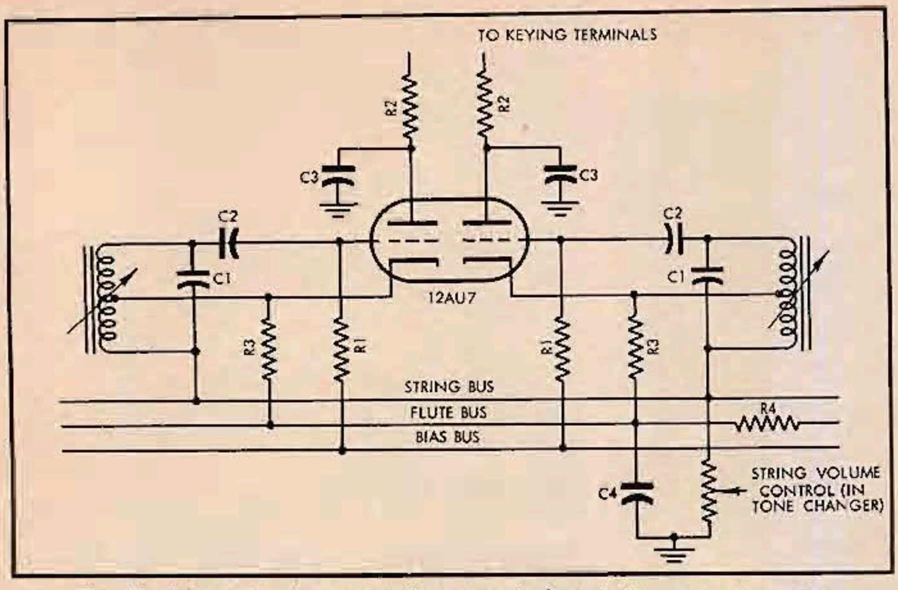

Fig. 11. Schematic of a portion (two notes) of an Artisan tone generator.

There are two groups of organs which use vacuum tube (or transistor) oscillators as the tone source in the organ. In the first type, one oscillator is used for all C's, another for the C#'s, and so on. Thus, twelve oscillators are required. The other C's, C#'s, etc. are obtained by frequency-division techniques which will be described later. Baldwin, Schober, Kinsman, and others use frequency division. In the second group, each tone in the entire instrument has its own separate oscillator. Conn, Allen, Artisan, and others use this design.

What are the relative advantages? Tuning is less time consuming when only twelve oscillators are involved. This means, however, that all C's, C#'s, and so on are always locked in phase. Some organists feel that such a scheme robs these instruments of a richness in tone. Others feel that in chord playing, the in-phase relationship for the doubled note is outweighed by all of the other random phased notes in the chord. When twelve oscillators only are required, high-quality components can be used to create extremely stable oscillators. Alan Douglas in his article (Reference 8) discusses the relative merits of frequency division *vs.* individual oscillators. In the final analysis, as always, the sounds of the organ should be basis of judgement rather than the circuitry.

Figure 6 is a complete schematic of one of the twelve Schober Concert Organ tone generators. V_{1a} is the master oscillator, a modified grounded-plate Hartley, which operates at the frequency of the highest note. The oscillator is tuned by adjusting the slug in L_1. The design utilizes the techniques for stability discussed earlier. The oscillator output is used only to drive the locked frequency dividing blocking oscillators, consisting of the seven remaining triode sections.

Assume for a moment that neither R_1 nor C_6 is connected to the plate of V_{1B}. The pulse transformer, T_1, has a low inductance value and is so connected that a positive pulse at the plate will put a negative pulse on the grid. When the circuit is first turned on, a small random signal will appear on the grid. If this signal happens to be positive, this will result in a much larger negative signal on the plate because of the high tube amplification. This causes the grid to draw a large sharp pulse of current. The current passes through the resistance of R_3 and R_{3A} in series, thus creating a large voltage drop across the resistance with the negative voltage at the grid. The negative voltage charges up the two capacitors C_4 and C_5 in series, and the tube is cut off.

This fast negative capacitor *charge* corresponds in time to the "flyback" or vertical portion of a sawtooth wave. The capacitors can *discharge* only through the resistors. Time for discharge is relatively slow and corresponds to the diagonal part of the sawtooth wave. As soon as the capacitors have discharged sufficiently to take the grid voltage above the cutoff point, the cycle begins again.

To avoid loading the master oscillator, the first blocking oscillator is synchronized to and thus controlled by the master oscillator. This is done by feeding d.c. to the master oscillator plate through the plate winding of T_1, and setting the R (R_3 and R_{3A}) and C (C_4 in series with C_5) of V_{1B} for a free-running frequency somewhat below the final frequency desired. When a negative oscillator pulse passes through the winding, it adds to the negative pulse beginning to build up because of the block-oscillator action and fires the blocking oscillator. Since the blocking oscillator fires once per master oscillator cycle, the frequency outputs of the two are identical.

The next blocking oscillator V_{2A} operates in the same way as the first with two exceptions. First, its R and C are chosen for a free-running frequency slightly less than half of the first stage. Second, synchronizing pulses are fed to its plate from V_{1B} through C_6. This stage, therefore, produces a frequency exactly half that of V_{1B}, or one octave below it. All of the remaining blocking oscillators divide in the same way. The variable factor is the amplitude of the sync for which the trimmers C_6, C_9, C_{12}, C_{15}, C_{18} and C_{21} are used.

The 18,000-ohm resistors, R_{10} through R_{16}, place a constant load across the output so that the changes between no load and the load imposed when a tone is keyed will be a minimum. The resistors also serve to keep the capacitors discharged so that they will not cause clicks or pops when the tones are keyed.

Conn's engineering approach (and also that of the Allen and Artisan instruments) is to provide separate keyed oscillators for each note in the scale, all running without any synchronization. This corresponds to the choral effect of the air organ. Conn employs a Hartley type oscillator which provides both pulse and flute (sine) tones.

Figure 7 shows the construction of a Conn tone-oscillator family and the schematic corresponding to this structure is shown in *Fig.* 8. Note that two wave shapes are derived from each oscillator, depending on the method of pulling them from the circuits. *Figure* 9 shows the oscillator chassis installed in the organ. A complete description of the Conn family of organs is given in AUDIO, September and October, 1956, (Reference 9).

Figure 10 shows eight sets of two-channel tone-generator assemblies assembled in the Artisan, which, similar to the Conn tone generator, takes two wave shapes from the oscillators rather than one sawtooth or square wave. Tuning is accomplished by changing the air gap and consequently the inductance, of the coil. *Figure* 11 is the schematic and *Fig.* 12 shows the wing nut arrangement for changing the air gap. Windings in the coil are arranged to obtain two different basic wave forms from each oscillator; a "flute" (sine) wave, and a "string" (pulse) wave.

To be continued

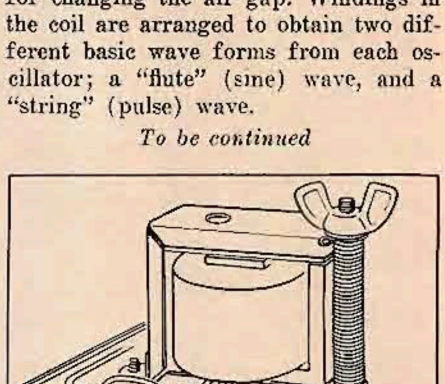

Fig. 12. Coil assembly showing tuning mechanism for Artisan organ.