

THE NOVACHORD

By FREDERIC D. MERRILL, JR.

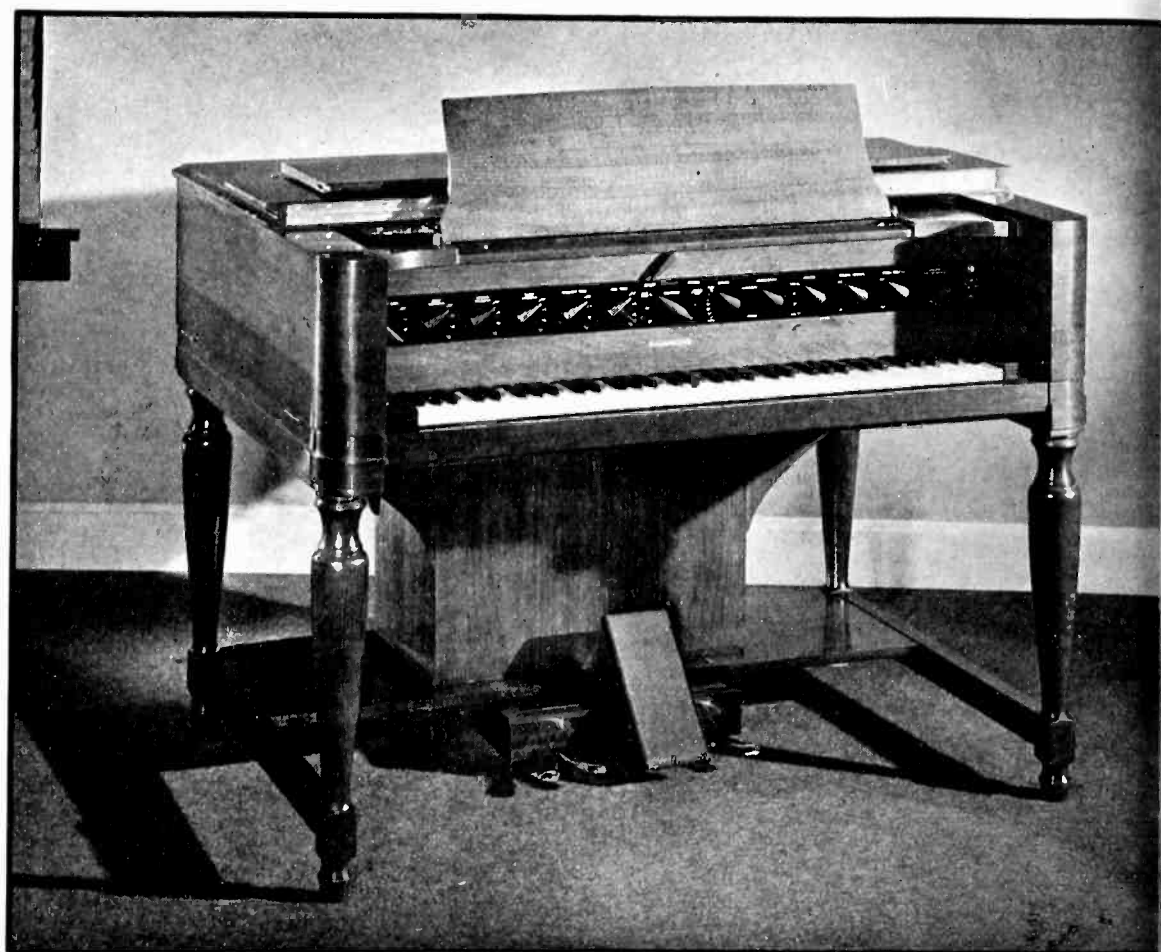
FURTHER evidence that the art of electronics is occupying an increasingly important role in the field of instruments for creating music directly is presented in the recently introduced Hammond Novachord.

To duplicate even partially its musical effects from conventional non-electronic instruments would require many of the tonal resources of a church pipe organ, piano, orchestra brasses, woodwinds, harp, and bowed strings. Although not intended to duplicate any existing musical instrument, the Novachord, shown in Fig. 1, accomplishes all this with a single simple keyboard playing technique and occupies as little space as a 4½-foot square.

Vacuum tube oscillators for producing musical tones have been suggested many times¹, but the problems of frequency drifting, timbre variety and proper amplitude-time starting and decaying characteristics to simulate organ or percussive qualities for a keyboard chordal instrument have necessitated the use of many tubes in a tremendous complexity of circuits. Consequently the design of a practical commercial model of small size and low cost that could be made in mass production represents an outstanding achievement in electronics engineering.

Principle of Operation

The present device² contains 163 vacuum tubes, most of which are arranged within the easily accessible shielded compartments of the main chassis for generation and control of the alternating current. This chassis is shown in Fig. 2. There are no strings, hammers, reeds, or



organ pipes in the generator system, in fact no moving parts except the vibrator pendulums.

The twelve top octave frequencies are generated by separate constant frequency audio oscillators operating continuously. There are no other oscillator tubes because all the lower frequencies are separated by octave intervals and furnished by novel frequency halvers, called dividers. Individual tone keying and determination of amplitude-time characteristics are performed in the control tube sections where the way in which the grid bias value varies from the

instant of keying is the important factor. With the exception of the top octave that needs no frequency dividers, there are two tubes, *i.e.* the divider and control tubes, associated with each of the 72 playing keys. Timbre regulation is accomplished both at the input to the 72 individual non-linear amplifier control tubes and also at common output multiple resonant circuits.

The Oscillator Units

The oscillator circuit for a single tempered frequency is shown in Fig. 4 and it is noted that the iso-



Fig. 1—Left, by the use of vacuum tube oscillators, the Novachord produces a wide variety of musical tones

Fig. 2—Above, a total of 163 tubes is used to generate and control the alternating currents which produce the tones

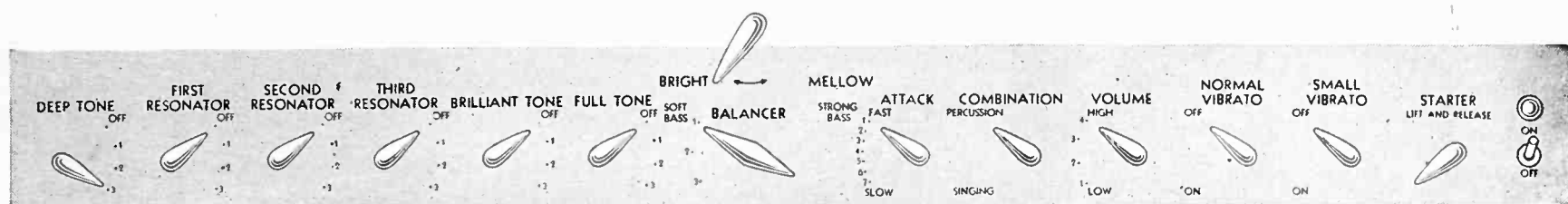


Fig. 3—Control board of the Novachord. By manipulation of the various controls, music similar to that of the pipe organ, piano, orchestra brasses, woodwinds and plucked and bowed strings may be produced

lation of feedback capacity resistance RC by a second triode section resembles a modified relaxation oscillator. The tuning coil L_1 is of special high Q construction to improve the frequency stability.

The output of the first triode is essentially sinusoidal in waveshape, one of the alternations having its peak lopped off somewhat. The second triode section gives an extremely rich harmonic output because the grid is operated nearly at cut-off². Two separated output points are used for isolation and also to be able to place a higher amplitude signal on the following divider tube.

As long as the various tube operating voltages have the same ratios, the frequency remains constant over a wide range in their actual magnitudes. This is realized in practice by the simple expedient of a common voltage divider so that line voltage changes as much as 80 to 130 result in no perceptible beat with another instrument on 110 volts. Naturally then the exact fre-

quency of supply line is also unimportant in affecting the oscillator frequency.

Tuning

Rough tuning is originally set by the condenser C_1 and fine tuning carried out by turning a knurled knob in one of the oscillator compartments to move in and out of the coil a single lamination and vary the permeability. Once an instrument has been installed the tuning remains satisfactory for many months except when the chassis receives severe shipping shocks or after long aging of tubes. Normally the original factory tuning makes an additional tuning at installation unnecessary. Unlike other frequency generating systems such as the conventional piano with strings or a single oscillator tube per tone, the octave tuning never gets out because of the frequency halving units controlled by the master oscillators. Therefore, obviously, only the temperament as set by the twelve con-

trolling oscillators need be adjusted.

The instrument is normally set at A 440 cycles per second at the factory but should it be necessary to retune to say A 444 then this can be accomplished in six minutes by the musician himself. First the A frequency is set according to that desired by the orchestra conductor. Then a jumper lead couples two control tube grids in second octave from top. Each oscillator is tuned by a clear zero beat formed by pure fourths and fifths, with the slight expansion of 4th and contraction of 5th for tempering the scale furnished by a single small fixed condenser bridging across the grid coil of the oscillator being adjusted. The closure error, or sum of all the errors from setting the individual oscillator frequencies is checked by beating the final E against the A starting point. If this beat rate is slow enough to be counted, then the

temperament is accurately adjusted.

Vibrato

The use of twelve master oscillators permits a frequency variation constituting a vibrato rather than the customary volume variation tremulant and since it is rare that two adjoining keys will be depressed simultaneously the number of vibrato units at the oscillators may be cut down to but six, one for each two consecutive generators.

These vibratos are set at slightly different rates so that the phase differences are constantly changing to produce a rich choir effect. The actual unit consists of reeds equipped with contacts to switch small condensers in and out of the tuned circuits. A compensating switch with correcting condenser maintains the mean frequency constant regardless of whether the vibrato rate is fast, slow or not in use at all.

There are twelve distinct frequency dividing systems corresponding to the twelve chromatic tones

of the octave; that is, one system provides all but one of the C octave tones, another all but one of the C# octave tones, etc. Within a given system there may be as many as five frequency halving units with a single pentode 6W7G to each unit. A given system consists of a series of these vacuum tubes connected together in cascade fashion and supplied at the input by one of the master oscillators. The outputs of each divider unit are also rich in harmonics. It is re-emphasized that these tubes are not oscillators for if the input signal is removed, then no output signal remains. Each tube acts as a non-linear amplifier.

The typical divider circuit illustrated in Fig. 5 merely passes plate current pulses for every other positive grid voltage alternation.

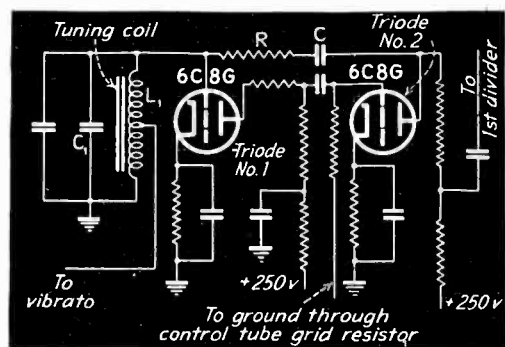


Fig. 4—Oscillator circuit for a single tempered frequency. L_1 is of high-Q construction to increase frequency stability

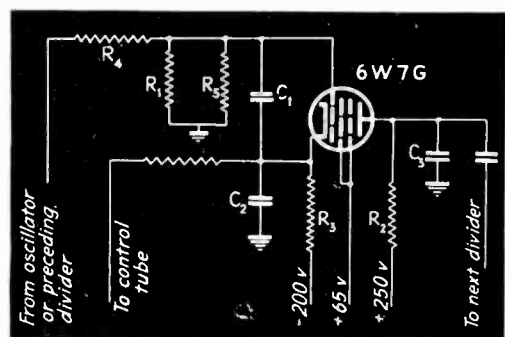


Fig. 5—Typical frequency divider circuit. Every other grid voltage pulse permits a passage of plate current

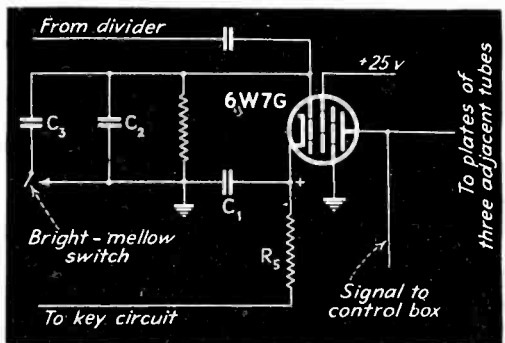


Fig. 6—Control tube circuit in which is generated a voltage rich in harmonics and which controls the brilliance of the tone

The arrangement resembles a self biased, cascade connected resistance coupled amplifier except for the circuit constants and the two additional condensers C_1 and C_3 . Owing to the self biasing of the tube, the cathode floats at a direct current potential with respect to ground so that the voltage between cathode and grid will be the cut-off voltage of the tube. Hence the direct current through the tube is practically fixed, almost entirely independent of the input signal and extremely small in average value.

One can thus consider the operation taking place at a point so close to cut-off that completely non-linear operation results. Naturally if the grid voltage goes only a minute degree positive with respect to cathode voltage, a sudden large surge of cur-

and C_2 are sawtooths, that at C_3 has the greater amplitude and slope and is therefore more effective in driving the next frequency halving unit.

It is interesting to note that an increase of the $R_1 R_2$ combination beyond the 1 to 3 megohm range may result in frequency being divided by three or a larger integer than the desired two. Below one megohm the output frequency may be the same as the input.

Envelope Control Tube and Circuit

The onset and decay of the musical tone are just as important as the harmonic content, for if the timbre is kept constant and only the amplitude-time characteristics altered, one may, for one example, pass through the surprising range of musical effects of a plucked string (guitar), a struck string (piano), a bowed string (violin) and even an organ tone. A rectangular beginning and ending envelope heard in an acoustically dead room is generally tiresome when used for an appreciable time and certainly unlike any familiar non-electronic instrument. Consequently it is desirable to have the envelope different from that given by sudden switching of a loudspeaker to a continuously operating alternating current generator.

For each key of the Novachord there is one control tube that allows not only wide latitude in the choice of envelope, but also the timbre. Even were the input to the control tube grid substantially sinusoidal, the output would still possess many harmonics because the grid bias is normally at cut-off so that only the positive peaks of signal voltage continuously applied are effective in producing plate current pulses². With playing key in up position the grid is so negative that no plate current results even though there is signal voltage on the grid. The electrostatic field of the grid is effectively blocked from affecting the plate by virtue of the intervening shield of the pentode.

Under normal conditions the input signal voltage to grid is sawtoothed so that the control tube acting as a non-linear distorting tube furnishes an extremely rich harmonic output. In the control tube circuit shown in Fig. 6 the use of C_2 alone gives a sufficiently brilliant string tone. The addition of C_3 serves to diminish the sharpness of

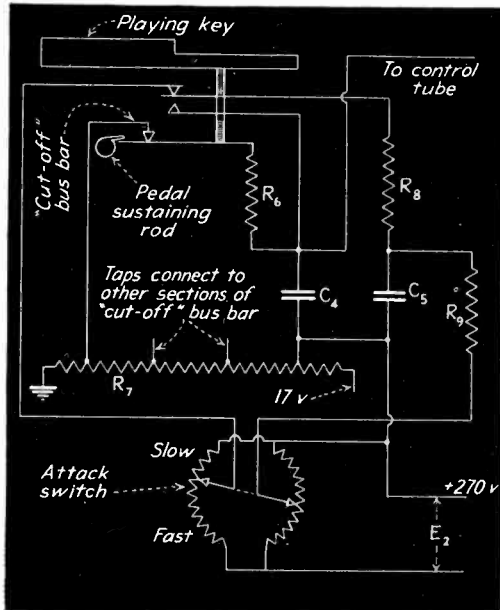


Fig. 7—This keying arrangement provides slow, medium and fast attack. Means for sustained tones is also provided

rent will take place. On the other hand any further increase of bias can only serve to reduce an already small plate current. Only alternate positive excursions of the grid are effective in producing plate current pulses because of the inter-dependence of the grid to cathode potential owing to the condenser C_1 , and the influence of C_2 in discharging owing to the rapid flow of cathode current to finally produce cut-off. The grid becomes sufficiently negative to prevent the following signal cycle from pulsing the plate but by the time the second input signal cycle arrives the grid potential has diminished enough to allow another short duration plate current pulse.

While both waveforms across C_3

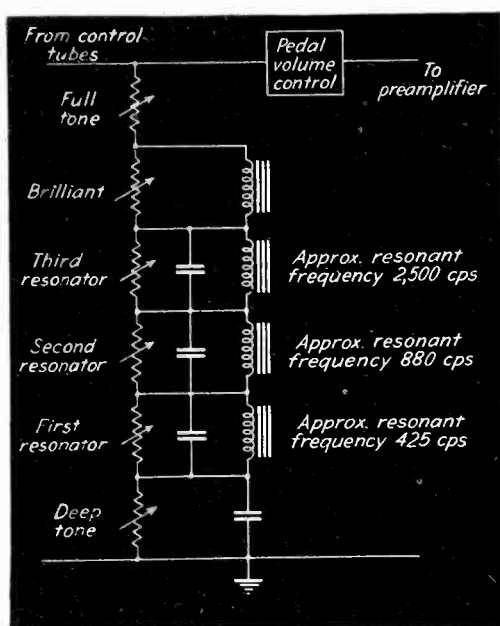


Fig. 8—The importance of the various parts of the musical tone range is controlled by the circuit shown here

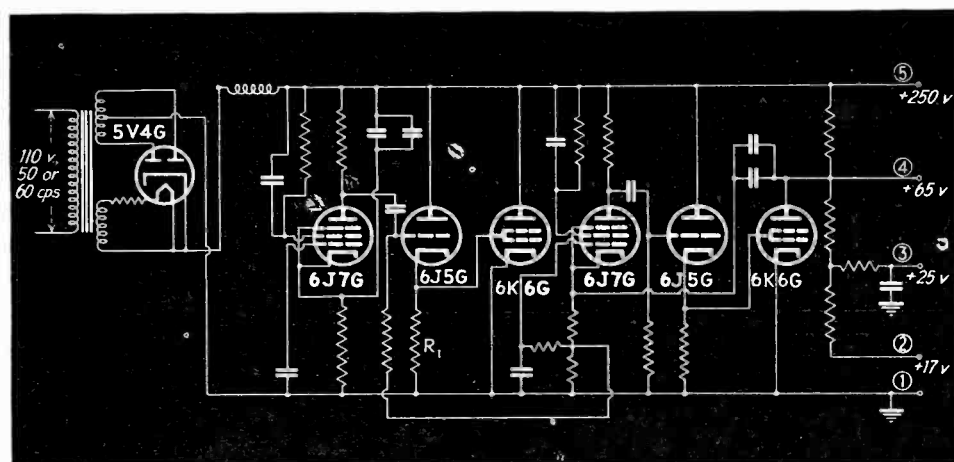


Fig. 9—The power pack which supplies 250 volts uses vacuum tubes for filtering in place of the condensers usually used for this purpose

the positive signal voltage alternation so that a more mellow timbre of weaker upper harmonics results. This "bright"- "mellow" switch is uni-controlled for the entire 72 tones, although the circuit arrangement is slightly different for the highest octave and none is used in the 18 bass control tubes.

The keying arrangement for the control tube circuit is given in Fig. 7 and permits both slow, medium, or fast attack as well as the sustaining of the tones through a foot pedal similar in effect to the piano pedal used to remove string dampers.

A brief explanation of the functioning is as follows. For organ effects the attack switch may be placed at "slow" so that condenser C_s has very little charge when playing key is up, owing to R_s being of much less resistance than R_o . When the key is depressed C_s charges up

slowly through R_o and in turn the increase of negative potential carried over to C_i through R_s , results in slowly diminishing the positive cathode potential, so that positive signal peaks are effective in producing very brief plate current pulses of increasing amplitude. The transient charging over, the plate current pulses continue constant in amplitude as long as the key remains depressed, since E_s provides a fixed bias value less than cut-off. If the key is now allowed to rise, E_s no longer passes bias potential along to C_i and on the contrary C_i is nearly discharged by R_s and C_i quickly returns to normal cut-off potential because of the shorting R_o . An organesque tone decay results. But should the sustaining pedal be depressed before the key is released,

Novachord does not permit control over the amplitude of the individual harmonics since the output from a single source, the control tube, is already rich in overtones. When it is remembered that many orchestral instruments are limited in pitch range and the timbre characterized by a group of adjacent harmonics being especially prominent, the electrical counterpart is provided by adding one or more inductive-capacity circuit elements tuned to different frequencies as shown in Fig. 8.

The "Full Tone" section alone will provide equal loudness for all the keys. The "Brilliant" portion accentuates the upper harmonics and thus the treble while the bass is weakened; the "Deep Tone" accomplishes the reverse. In this way the timbre and tone volume between bass and treble is balanced without any sudden discontinuities.

The keyboard range of fundamental frequencies to be reproduced is from 43.7 cycles per second to 2637 cycles per second, a full six

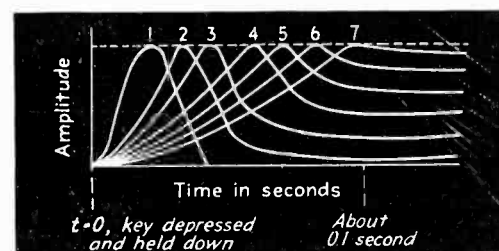


Fig. 10—Amplitude-time curves for attack switch positions

octaves. It is noted that the resonant frequency of the third tuned circuit is approximately 2500 cycles per second, just at this upper keyboard limit. Obviously harmonics of the fundamentals extend far beyond the 2637 value.

If one of the resonator circuits has its largest resistance setting and all other resistances are set at zero, then a given band of harmonics will be particularly emphasized. A setting of some resistance at the "Full Tone" will allow part of the regular output from control tubes to pass through unaltered as well as diminish the accentuation of a particular resonant frequency range by that resonator.

Although the keys are not touch responsive as the ordinary piano is, this is partly compensated for by the attack switch being set at position #3 or #4 to allow the tone volume from the longer held keys to

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The Novachord

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become weaker while the accentuated melody is being played. Also the panel "Balancer" control slightly increases or diminishes the volume of the lower half of the keyboard and the timbre controls are helpful. The action of the left sustaining pedal is split at center of keyboard so that only lower half may be sustained if desired.

The foot pedal volume control operates a 350 μ f variable condenser to vary the gain of a pre-amplifier tube through altering the plate to grid negative feedback. This eliminates the problem of the continuous wear of resistor switch points as well as forming a stepless variable.

As the loudspeaker is pointed towards the floor at a slanting angle, the high frequencies are diffused and the chance of a listener or player being located within the uncomfortable treble radiation cone lessened.

The power amplifier is a standard Hammond Organ amplifier, using two Type 56 input tubes and four Type 2A3 output tubes in push pull parallel. The power consumption of the entire self-contained instrument is 450 watts, less than what might be expected since the tubes are operated extremely conservatively.

Power Pack

The plate, screen and grid voltages for the oscillators, dividers and control tubes are exceptionally well filtered and isolated by a power pack employing vacuum tubes in place of the usual filter condensers.

Referring to Fig. 9 it is seen that the rectifier tube supplies 250 volts between terminals 1 and 5, with the filtering by the following three tubes. The action is explained as follows. If a small ripple appears in the 250 volt line it will be impressed on the cathode of the first filter tube, 6J7G, through the condensers and will be amplified by the next tube, 6J5G. The amplified ripple will then appear across R_1 and will drive the next tube which is the actual filter, and the plate current of this tube will change in such a way that it opposes the original ripple in the line and is of such value that it cancels it out. Any high frequency ripple introduced by the

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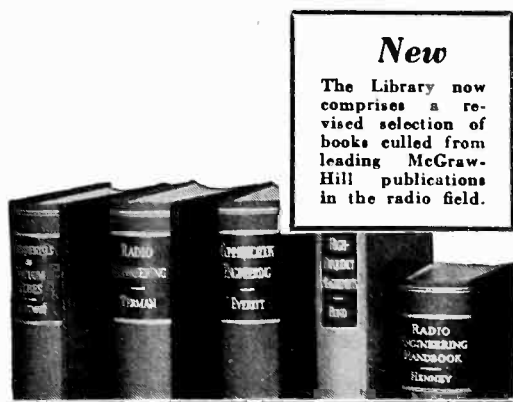
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oscillators into the power supply is also filtered out by this system. Tubes 5, 6 and 7 operate similarly for the 65 volt tap on the voltage divider network.

Because the voltage regulation of the output of the 5V4G and supply transformers is poor, the filter tube plates can be considered as operating primarily as variable loads rather than to supply a 180 degree out of phase hum bucking voltage.

Control Panel

The musician's control panel already shown in Fig. 4 will be generally understood from the foregoing description. The "combination" knob set at "percussion" instantly gives the piano effect by mechanically setting up the proper positions of the other knobs for correct piano timbre and envelope. At the "singing" position any previous set-up of knobs is cancelled out and a new combination immediately arranged mechanically, consisting of a mellow tone quality and organ-like attack. The volume knob position determines the maximum volume obtainable by full depression of the foot volume pedal. The Starter is necessary to insure the starting of the pendulum vibratos into motion.

The Novachord is the first commercial pure electronic musical instrument possessing a full keyboard on which chords may be played.

References

- (1) Lee DeForest, Patent 1,543,990. Coupleaux-Givelet. U. S. Patent 1,905,996 and others.
 - (2) For more detailed information refer to Laurens Hammond Patent 2,126,682. Additional material is found in 2,126,464 on control tube.
 - (3) Related art is found in G. Smiley Patent RE 20,825 and Re 20,831, 1938.
- For general information on the entire field read "Electronic Music and Instruments," B. F. Miessner, Proc. I.R.E., Nov. 1936. Vol. 24, No. 11.

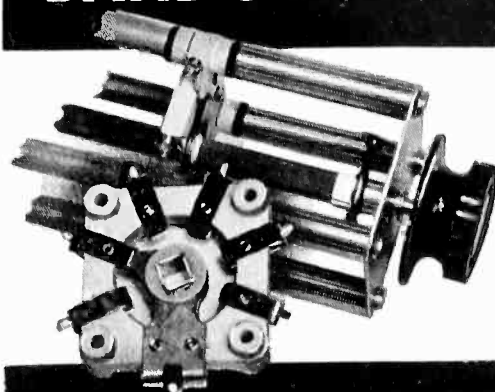
Bio-millivoltmeter

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former of the saturated field type. In order to produce further refinement in stability, the d-c power supply is shunted by a voltage regulator tube.

The probable error in stability due to variations in circuit elements is halved in this type of circuit as compared to the usual in-line resistance coupled amplifier since all the

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