Crystal-Controlled Oscillators

A Review of Modern Crystals, Circuits and Tubes

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A PERIODIC survey of the behavior of crystal-oscillator circuits is desirable because of the new types of crystals and tubes that appear over a period of time. Previous examinations of crystal-oscillator circuits by Lamb [1] and Goodman [2] resulted in much useful data pertaining to crystals and tubes of prewar design. Although the oscillator-tube complement has not grown appreciably since the time of the work by Goodman, considerable development was done in the crystal field during the years of wartime research. The crystals now commonly available on the regular and the surplus markets are smaller and therefore cannot handle as much power as those produced in the past and, as a result, the operating conditions of an oscillator circuit are now more critical.

The object of this latest investigation was the determination of optimum operating conditions for three popular oscillator circuits using the new type of crystals in conjunction with any one of four popular oscillator tubes. The circuits tested were the grid-plate, the Tri-tet, and the modified Pierce and the tubes were the Types 6AG7, 6F6, 6V6GT and 6L6. The operating characteristics sought after were good keying, low crystal current, reduction in the frequency shift normally caused by tuning of the plate circuit, and moderate power output at the fundamental and the harmonic frequencies.

For clarification it should be stated that good keying in this instance means a keyed signal free from chirp and that power output does not mean maximum obtainable power. In these tests power output was secondary to keying and frequency shift, and no attempt was made to generate more power than would be required to drive another receiving-type tube or a low-power transmitting tube such as the 807. During the test the 6L6 was operated at a higher input than the other three types of tubes but this was done to permit study of the crystals in a power circuit — not as an attempt to increase output.

The Test Equipment

The test equipment consisted of d.c. meters for measuring power input and oscillator output, two receivers, a frequency standard, an audio oscillator, an oscilloscope and, last but not least, a pair of 60-ma. pilot lamps. One of the receivers was used for monitoring the output signal of the oscillator and the second receiver was used in conjunction with the 'scope, the audio oscillator and the frequency standard to provide means of measuring the frequency shift. One pilot lamp, connected as shown in Fig. 1, was used to measure crystal current. During test runs, the brilliance of this lamp was compared with that of the second lamp which was in turn connected in a circuit consisting of a battery, a meter and a potentiometer. Inasmuch as the filaments of 60-ma. bulbs do not become incandescent with a current of less than 30 ma., the performance curves of the oscillators do not show crystal currents less than this value. Fortunately, these unmeasurable currents are *safe* currents.

The Test Unit

In the test unit all values of *C*, *R* and *L* were made variable so that optimum circuit values could be readily determined. A Type 807, connected as shown in Fig. 1A, was used as the oscillator load. The tube load allowed study of the keying and the other characteristics of the oscillators under normal working conditions. Incidentally, output data for the oscillators are expressed in terms of rectified current measured at the grid of the 807. Dials for the feed-back condensers were calibrated in terms of capacitance and the plate-circuit control was calibrated in terms of frequency. These calibrations permitted rapid logging of the circuit values for different sets of operating adjustments.

Input to the Types 6AG7, 6F6 and 6V6GT was approximately 5 watts in all cases and the input to the 6L6 was around 10 watts. The output of the plate supply was controlled by a Variac and the screen voltage for the tubes was held constant by a VR-150 regulator tube.

It was decided at an early stage of the game to make the keying, frequency-shift, crystal-current and power-output measurements with 7-Mc. crystals providing the fundamental frequencies. It was felt that the 7-Mc. crystals might be a little more tricky to handle than the 3.5-Mc. crystals and we wanted to make the tests as conclusive as possible. However, 3.5-Mc. crystals were used for obtaining the harmonic data because more reliable checks could be made in the

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[1] Lamb, "A Practical Survey of Pentode and Beam Tube Crystal Oscillators for Fundamental and Second Harmonic Output," *QST*, April, 1937.

[2] Goodman, "Keying the Crystal Oscillator," *QST*, May, 1941.

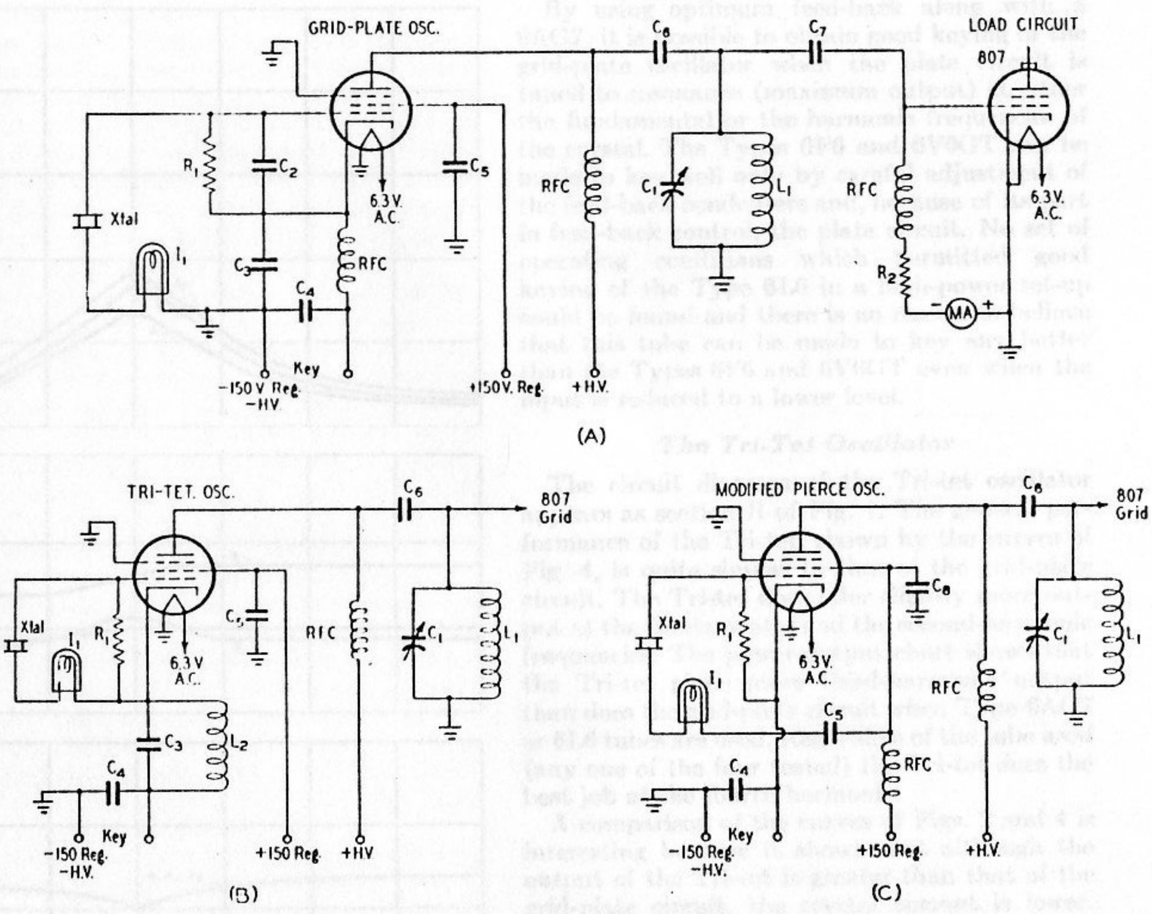

Fig. 1 — **Circuit diagrams of the crystal oscillators.**

C_1 — 250-μμfd. variable.
C_2, C_3, C_8 — Feed-back control condensers (see text and Figs. 2, 3, 4 and 5).
C_4, C_5, C_6 — 0.005 mica.
C_7 — 100-μμfd. mica.
R_1 — 0.1 megohm, ½ watt.
R_2 — 15,000 ohms, 10 watts.
L_1, C_1 — Tuned to crystal frequency or desired harmonic.
L_2, C_3 — Tuned above crystal frequency (see text).
I_1 — 60-ma. pilot lamp.
MA — Grid-current milliammeter.
RFC — 2.5-mh. r.f. choke.

range up to 14 Mc. than could be made if the range extended up to 28 Mc.

As work progressed a set of fixed circuit values was arrived at and these values appear in the parts list of Fig. 1. The values apply to all three circuits and are optimum for good keying, minimum frequency shift and output at the fundamental and the harmonic frequencies. Circuit values that apply to a single circuit are listed along with the performance curves of Figs. 2, 3, 4 and 5.

General Conclusions

The results of the oscillator tests are best presented by the curves of Figs. 2 to 5, inclusive. However, additional data of a general nature apply to all three circuits and this material will be covered before the individual circuits are discussed.

The circuit diagrams of Fig. 1 show the use of regulated screen voltage. (Actually, it might be more correct to say regulated *plate* voltage because the screen grid serves as the oscillator plate in each of the circuits shown.) The value of this voltage, 150 volts, was determined by the oscillator output when a 250-volt plate supply was used. Lower screen voltages reduced the output and higher voltages contributed nothing more than an increase in crystal current. The regulated screen voltage has two desirable effects: it provides a noticeable improvement in keying and makes the power output of the oscillator more independent of plate voltage. Cathode current of a screen-grid tube is largely controlled by the screen voltage, and with this voltage held constant there is less change in plate current as the plate voltage is swung around a given value. With the test circuits shown it was possible, by means of the Variac, to swing the plate voltage approximately 100 volts above and below the regular value without affecting keying, frequency shift or output to any significant extent.

The output from each of the circuits was greatest when a low-*C* plate tank was used. This feature is of particular interest when harmonic output has importance. Usually, it is desirable to obtain nearly equal output at the fundamental and the second-harmonic frequencies and this condition cannot be obtained with a low-C tank circuit at both frequencies. However, a single tank circuit that can be tuned over two bands will give the desired effect, because the resulting high-C at the fundamental reduces the output at that frequency, a condition that usually can be tolerated. In one series of tests, when separate plate coils were used for each band, oscillator output at the fundamental frequency was nearly twice that obtained at the second harmonic. Changing over to a two-band tank lowered the output (expressed in terms of 807 grid current) from 12 to 9.8 ma. at the fundamental but increased the second-harmonic output from 6.3 to 8.2 ma.

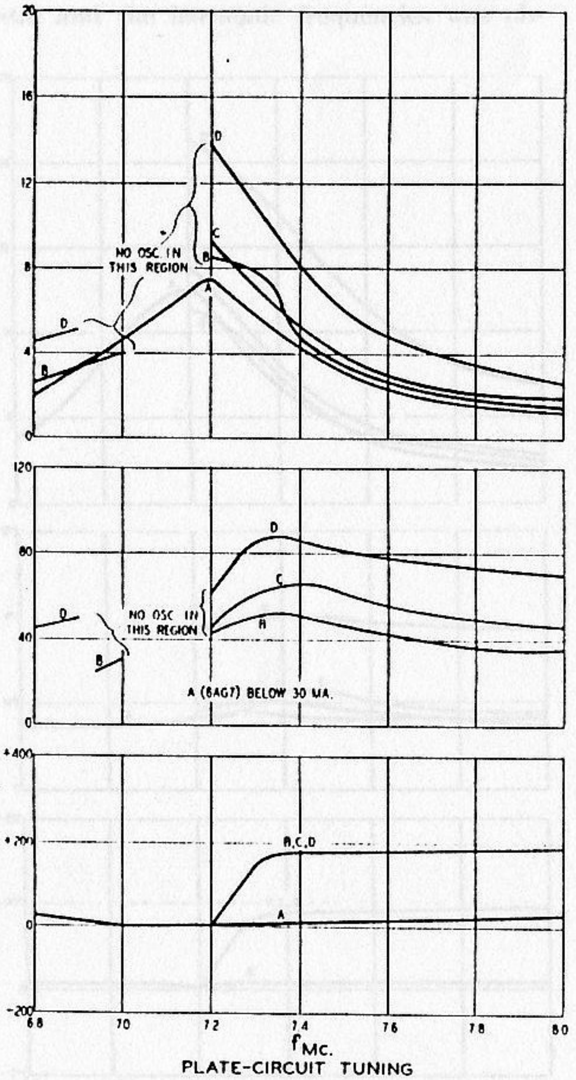

Fig. 2 — Showing crystal current, relative output and frequency shift of the grid-plate oscillator when optimum circuit adjustments are made. Curves *A*, *B*, *C* and *D* are for the Types 6AG7, 6F6, 6V6GT and 6L6, respectively. Critical circuit values for the 6AG7 are: C_2 = 10 $\mu\mu$fd.; C_3 = 220 $\mu\mu$fd. C_2 and C_3 for the other tubes are 25 and 100 $\mu\mu$fd., respectively.

A high value of grid-leak resistance was selected for the following reasons: (1) better keying as indicated by less chirp, (2) less crystal current, (3) a reduction in d.c. input (less cathode current) without affecting plate-circuit output, (4) it eliminated the need for the customary grid-circuit r.f. choke. The resistance can be lowered to approximately 50,000 ohms before grid loading becomes great enough to warrant use of a choke.

Plate-circuit keying of the oscillators proved to be slightly less chirpy than did straight cathode keying. Plate-circuit keying is accomplished by returning the grid leak to cathode rather than to ground. This arrangement has one disadvantage in that the key is hot with B+ when the circuit is open. Anyone interested in experimenting with other types of oscillator keying should study the article by Goodman.[2]

Although a lamp bulb connected as shown in Fig. 1 serves well as a crystal-current indicating device, it should not be used as a permanent part of a keyed oscillator circuit. The resistance of a lamp varies as the current through the lamp is increased or decreased by, for instance, keying. This variable resistance affects the activity of the crystal as indicated by a chirp that can be eliminated only by removing the bulb from the circuit.

The Grid-Plate Oscillator

Circuit A of Fig. 1 is different from the grid-plate circuit shown in the *Handbook* only in that it includes an external feed-back condenser, C_2, between the grid and the cathode of the tube. This condenser and C_3 form a voltage divider across the crystal and by adjusting the ratio of the two capacitances it is possible to control the feed-back.

Operation of a circuit with both optimum and improper feed-back is shown by the curves of Figs. 2 and 3. Fig. 2, showing optimum operation, indicates that low crystal current, minimum frequency shift and maximum output are obtained with a low value of C_2 and a fairly large value of C_3. This same capacity ratio results in maximum harmonic output and clean keying.

With a really active crystal working along with a Type 6AG7 tube, it is possible to depend on the grid-cathode capacitance of the tube as the grid-cathode section of the feed-back divider. However, an external condenser — a 15-$\mu\mu$fd. variable would be best — will permit optimum adjustment for all grades of crystals.

Study of Fig. 2 will show that the Types 6F6, 6V6GT and 6L6 — all popular oscillator tubes — do not compare favorably with the 6AG7. It will be noticed that the feed-back requirements (a lower ratio between C_2 and C_3) are greater, that the crystal current is higher and that the tubes oscillate only when the plate circuit is tuned

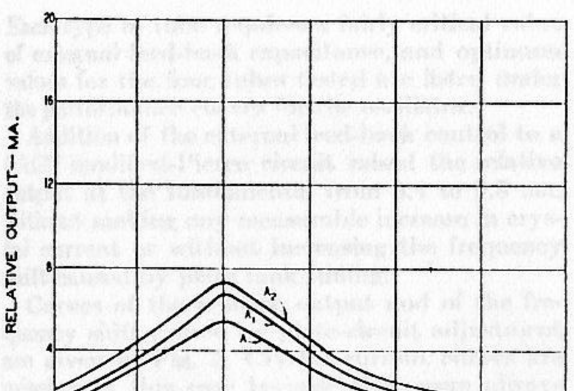

Fig. 3 — Curves showing the effect on the operating characteristics of a 6AG7 grid-plate oscillator when the feed-back is not optimum. The excessive crystal current and increased frequency shift also occur in the other circuits under similar conditions. Feed-back capacitance values associated with the three curves are:

A — $C_2 = 75$ $\mu\mu$fd.; $C_3 = 10$ $\mu\mu$fd.
A_1 — $C_2 = 75$ $\mu\mu$fd.; $C_3 = 220$ $\mu\mu$fd.
A_2 — $C_2 = 10$ $\mu\mu$fd.; $C_3 = 10$ $\mu\mu$fd.

to the high side of resonance. Furthermore, as shown by Fig. 2, the plate-circuit tuning has considerable control over crystal current, frequency shift and, naturally, power output. All of this means that tuning to the high side of resonance gets to be a delicate operation.

The curves of Fig. 2, by showing how the frequency is pulled as the plate tanks for the various tubes are tuned through resonance, clearly demonstrates the superior isolation qualities of the 6AG7 as compared with that of the other three tubes.

The harmonic-generating capabilities of the grid-plate oscillator are listed with those of the Tri-tet and the modified Pierce in Table I.

By using optimum feed-back along with a 6AG7, it is possible to obtain good keying of the grid-plate oscillator when the plate circuit is tuned to resonance (maximum output) at either the fundamental or the harmonic frequencies of the crystal. The Types 6F6 and 6V6GT can be made to key well only by careful adjustment of the feed-back condensers and, because of its part in feed-back control, the plate circuit. No set of operating conditions which permitted good keying of the Type 6L6 in a high-power set-up could be found and there is no reason to believe that this tube can be made to key any better than the Types 6F6 and 6V6GT even when the input is reduced to a lower level.

The Tri-Tet Oscillator

The circuit diagram of the Tri-tet oscillator appears as section B of Fig. 1. The general performance of the Tri-tet, shown by the curves of Fig. 4, is quite similar to that of the grid-plate circuit. The Tri-tet does offer slightly more output at the fundamental and the second-harmonic frequencies. The power-output chart shows that the Tri-tet gives more third-harmonic' output than does the grid-plate circuit when Type 6AG7 or 6L6 tubes are used. Regardless of the tube used (any one of the four tested) the Tri-tet does the best job at the fourth harmonic.

A comparison of the curves of Figs. 2 and 4 is interesting because it shows that although the output of the Tri-tet is greater than that of the grid-plate circuit, the crystal current is lower. The one exception to this rule is caused by the use of a Type 6AG7 in which case the Tri-tet still gives the most output but at a higher crystal current than the other circuit.

Considerable time was spent working with the cathode circuit of the Tri-tet oscillator and the conclusions reached are as follows: (1) A high-C circuit is best from the [illegible]point of both crystal current and output. (2) The circuit should be tuned to a frequency somewhere between the

TABLE I

Relative Harmonic Output — Ma.

Harmonic	*Grid-Plate*	*Tri-Tet*	*Mod. Pierce*	*Tube*
2nd	5.6	8.2	6.6	6AG7
3rd	3.2	4.3	4.1	
4th	1.3	2.0	1.2	
2nd	6.6	8.5	see text	6F6
3rd	3.0	2.3		
4th	0.	1.2		
2nd	7.0	8.2	see text	6V6GT
3rd	2.8	2.6		
4th	1.2	1.5		
2nd	12.5	16.0	see text	6L6
3rd	5.5	13.4		
4th	2.8	6.0		

fundamental and the second-harmonic frequencies. (3) A fixed tuned circuit is a practical as well as a convenient arrangement to use for output at both the fundamental and the harmonic frequencies.

By a high-*C* circuit we mean one that employs approximately 250 μμfd. when tuned for operation with 3.5-Mc. crystals. A value of 150 μμfd. is suitable for use with 7-Mc. crystals.

The frequency at which the cathode circuit should be tuned was determined by a series of test runs made while using a variable-frequency circuit. These tests seemed to indicate that with some tubes it is advisable to tune the cathode slightly above the crystal frequency and that other tubes operate best with the cathode tuned to the second or even the third harmonic. However, an r.f. indicator coupled to the plate tank showed that maximum output at the fundamental and the harmonic frequencies was obtained with the cathode tuned approximately midway between the fundamental and the second-harmonic frequencies. Output at the crystal frequency will have high harmonic content if the cathode is tuned near any one of the harmonics. When the plate tank was adjusted to a harmonic frequency, it was not possible to increase output by retuning the cathode to a higher frequency nor did the r.f. indicator show an excessive amount of fundamental present in the output.

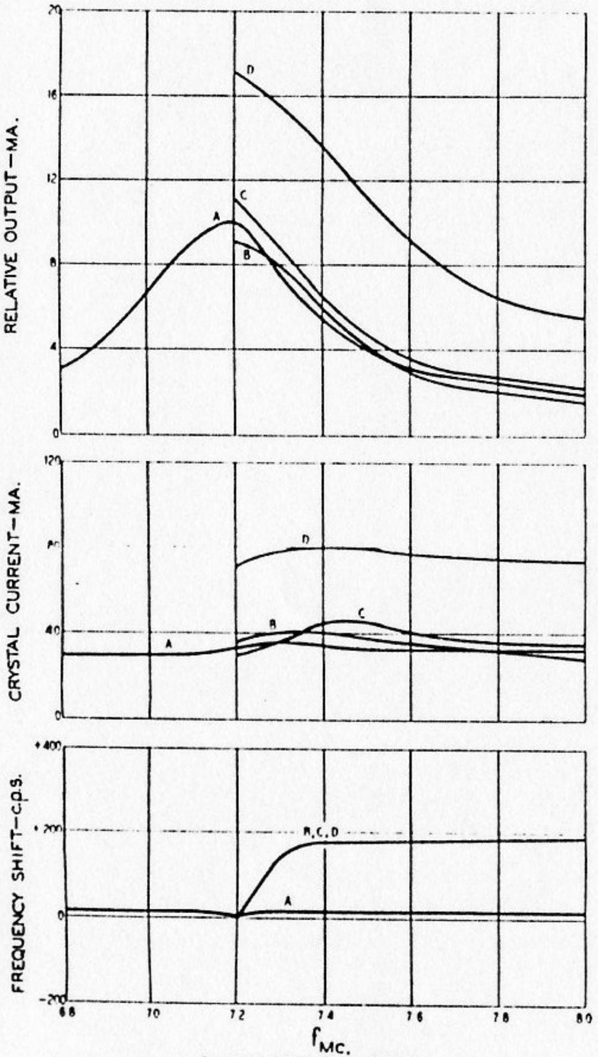

Fig. 4 — Performance curves for the Tri-tet oscillator. See text for critical circuit values. *A*, *B*, *C* and *D* refer to the 6AG7, 6F6, 6V6GT and 6L6, respectively.

There does not appear to be a *spot* frequency (for a particular crystal) to which the cathode must be tuned. If, however, the circuit is made variable to facilitate maximum power output over a wide range of crystal frequencies, it should not be capable of tuning down to the crystal frequency. This adjustment results in excessive feed-back which, in turn, causes dangerously high crystal current, frequency creeping and reduced output. Tubes other than the Type 6AG7 won't even start to oscillate consistently with the cathode set too close to the crystal frequency.

Tuning of the plate circuit of the Tri-tet oscillator using a Type 6AG7 tube causes slightly less frequency shift than does the tuning of a grid-plate circuit using the same tube. A comparison of Figs. 2 and 4 proves this point and also shows equivalent frequency-shift curves for the two circuits when the Types 6F6, 6V6GT and 6L6 are employed. Also pointed out by Fig. 4 is the fact that the plate circuit of the Tri-tet must be tuned to the high side of resonance when tubes other than the 6AG7 are used. From these curves it is also obvious that plate-tank tuning has an effect on feed-back.

Some frequency shift does occur when the cathode circuit of a Tri-tet is tuned in the vicinity of the fundamental or the harmonic frequencies. This information is not presented in curve form because it represents an improper circuit adjustment which should be avoided.

Use of the Type 6AG7 tube in a Tri-tet oscillator assures keying free from chirp even when the plate tank is adjusted for maximum output, and frequency shift is almost negligible with this arrangement. Types 6F6 and 6V6GT key well only at the expense of reduced output, because of the necessity for tuning the plate tank off resonance. There is no set of circuit adjustments which permits chirp-free keying of the high-power 6L6 circuit.

The Modified-Pierce Oscillator

The circuit diagram of the modified-Pierce oscillator is given in Fig. 1C. Ordinarily, variation in screen voltage provides the primary means of adjusting feed-back in this circuit. However, if regulated screen voltage is to be employed in the interests of good keying, it is necessary to find another method of regulating the feed-back. This can be accomplished by adding a fixed capacity, C_8 of Fig. 1C, between screen grid and ground.

Each type of tube requires a fairly critical value of external feed-back capacitance, and optimum values for the four tubes tested are listed under the performance curves for the oscillator.

Addition of the external feed-back control to a 6AG7 modified-Pierce circuit raised the relative output at the fundamental from 6.4 to 9.8 ma. without making any measurable increase in crystal current or without increasing the frequency shift caused by plate tank tuning.

Curves of the relative output and of the frequency shift caused by plate-circuit adjustment are given in Fig. 5. Crystal current curves are missing in this case because they were always below the measurable value of 30 ma.

The operational curves show an interesting trait of the modified-Pierce oscillator. Although the 6AG7 reacts to plate circuit tuning just as it does in the other two circuits, the other three tubes require that the plate tank be adjusted to the *low-frequency* side of resonance when 7-Mc. crystals are used. Not shown by the curves is the fact that these same tubes require a plate-circuit adjustment on the high side of resonance when 3.5-Mc. crystals are used. This is possibly due to a change in feed-back conditions as the frequency of operation is increased. In any event, we have learned that the plate-tank of the Pierce circuit requires the same careful tuning as the plate circuit of the other oscillators.

Harmonic output data for the Type 6AG7 tube operated in the Pierce circuit are listed in Table I. Harmonic output delivered by the other three tubes was so low as to be of no practical use and, as a result, the output figures are not listed. As a matter of fact, some of the tubes would not oscillate when the plate tank was tuned very far off the fundamental frequency.

In conclusion, we can say that the modified-Pierce oscillator is a simple, practical circuit so long as the Type 6AG7 tube is used. With this tube, it will key well when adjusted for maximum output and the harmonic output capabilities are comparable with the other two circuits. Use of the modified-Pierce in conjunction with Types 6F6, 6V6GT and 6L6 is not recommended if either good keying or harmonic output are design considerations.

Summary

In summary, the following should be considered in the selection of any one of the three circuits discussed above:

1) Regardless of the circuit selection, use regulated screen voltage if good keying is desired.

2) Of the four tubes tested, the 6AG7 is by far the best from every standpoint.

3) The Tri-tet oscillator gives the most output (at both the fundamental and harmonic frequencies). The modified Pierce is second in this respect, so long as a Type 6AG7 tube is used.

4) The modified-Pierce circuit is easiest on the crystals and, except when a 6AG7 is used, the grid-plate oscillator operates with the highest crystal current.

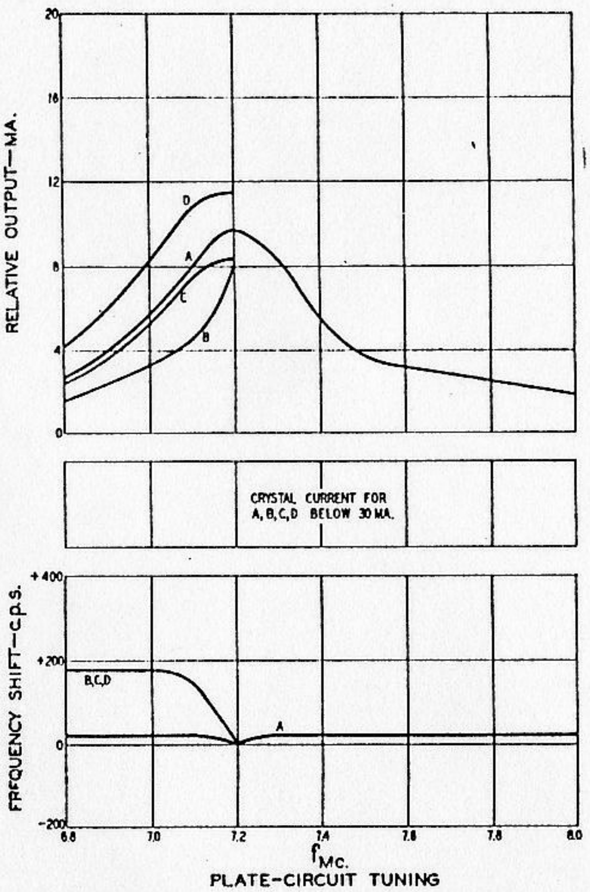

Fig. 5 — Crystal-current, frequency-shift and output data for the modified-Pierce oscillator. Feed-back capacitances (Cs) for the various tubes are: 6AG7 = 220 μμfd.; 6F6 = 40 μμfd.; 6V6GT = 50 μμfd.; 6L6 = 60 μμfd.

5) With a tube other than the 6AG7 in use, it is not advisable to tune any of the oscillators for maximum output because a slight change in circuit conditions may cause frequency shift.

6) Plate-circuit keying of the circuits results in less chirp than does the use of straight cathode keying.

7) Remember — the use of a crystal doesn't automatically assure a good sounding note. But the crystal is willing to do its part — if you'll give it the chance.

Strays

W1AGM and W4GJW report that their directory of doctor and dentist radio amateurs is rapidly taking shape. If you are a U. S. or foreign amateur engaged in these professions and haven't already done so, you are requested to communicate with W4GJW, Dr. Arthur W. Woods, Woodward Building, Birmingham, Ala., before the directory's deadline of May 1st.