

## NOTES ON THE PLATE EFFICIENCY OF POWER OSCILLATORS

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## ABSTRACT

This paper presents several considerations which are usually overlooked by designers of power oscillators. Effects of the shape of the path of operation upon the plate efficiency of the oscillators are discussed and methods of improving the plate efficiency are mentioned.

## 1. INTRODUCTION

A power oscillator may be considered as a converter which converts d.c. power into a.c. power. It is generally accepted as a correct statement that the main difference between a power amplifier and a power oscillator lies in the fact that the latter is a self-driven device, that is, the driving power in the grid circuit is supplied not from the output of the preceding stage but from the output of the oscillating circuit itself. While there is nothing wrong with this statement, it is sometimes unfortunate that it leads one to think that this is the only main difference to be considered in the design of the oscillator. Designers of power oscillators, believing that the driving power is the main consideration, proceed with the conventional design of a power amplifier,<sup>1</sup> calculate the power input and output, the driving power required, and the plate efficiency, and finally deduct the driving power from the power output and call this difference the power output of the oscillator. To their surprise, the actual performance of the oscillator so designed never could live up to the standard as predicted on paper. The predicted plate efficiency may be as high as 80%, for it is not at all a difficult task to design a class C power amplifier with plate efficiency of 85% and requiring a driving power which may be only 2 or 3 percent of its output power. Actually, however, an

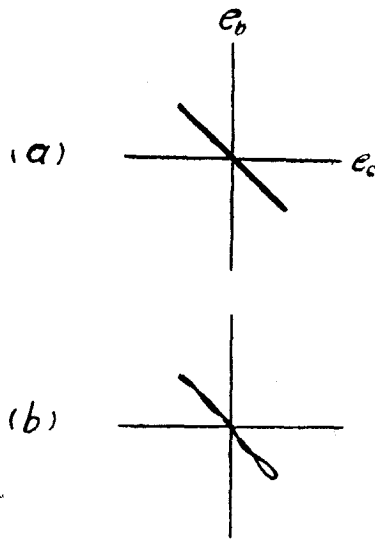
1. See for example, R. I. Sarbacher, "Graphical Determination of Power-amplifier Performance", *Electronics*, December, 1942.

oscillator so designed may be found to have an efficiency as low as 60% or less. A design engineer is often perplexed at this relatively large difference between actual performance and pre-determination on paper. The purpose of this paper is to point out that, as far as efficiency and general performance is concerned, the driving power consideration is the least important and that there are at least three other reasons why the performance of an oscillator is inherently less efficient than an amplifier. These are:

- (1) the consideration of phase angle and its effect on the path of operation,
- (2) harmonic content and its effect on the path of operation and
- (3) the difficulty of making proper adjustments to realize a proper design on paper. Proper design procedures, comparison of different kinds of tuning indicators and various possible ways and means of improving the plate efficiency will also be mentioned.

## 2. EFFECT OF PHASE ANGLE

The plate efficiency of the tube depends entirely on the location and shape of the path of operation. Fig. 1 shows a few examples of the



shape of the paths of operation of a power tube on the  $e_b$ — $e_c$  (plate voltage-grid voltage) plane. Fig. 1a shows the path of operation of a tuned class C amplifier with both grid and plate circuits tuned to the same frequency. The phase angle between  $e_b$  and  $e_c$  is 180 degrees and hence the path of operation is a straight line. The origin of the coordinates corresponds to the quiescent point of operation determined by the plate supply voltage  $E_{pb}$  and the grid bias  $E_{gc}$ . This path may be superimposed upon the static characteristics of the tube drawn in the same plane and the power output, input, plate efficiency may all be calculated by

using some suitable schedule of harmonic analysis<sup>2,3,4</sup>. Using "15 point analysis", the d.c. component, the amplitude of the fundamental component and the amplitude of the second harmonic of the plate current are respectively given by

$$I_{b0} = \frac{1}{12} \left( \frac{i_1}{2} + i_2 + i_3 + i_4 + i_5 + i_6 \right), \quad (1)$$

$$I_{p1m} = \frac{1}{12} (i_1 + 1.93 i_2 + 1.73 i_3 + 1.41 i_4 + i_5 + 0.26 i_6), \quad (2)$$

$$I_{p2m} = \frac{1}{12} (i_1 + 1.73 i_2 + i_3 - i_5 - 1.73 i_6), \quad (3)$$

where  $i_1, i_2$ , etc. are instantaneous currents chosen at 15 degree intervals,  $i_1$  being the current at the end point of the path of operation. Fig. 2 shows the plate current static characteristics and also two possible paths of operation, one corresponding to Fig. 1a and another corresponding to Fig. 1c.

Fig. 1c shows an elliptical path of operation. This is the case with a detuned amplifier. Comparing this with the straight line path as shown in Fig. 2, it is obvious that the d.c. component for the elliptical path is much larger for

2. J. E. Mourontse II and H. N. Kozanowski, "Analysis of the Operation of Vacuum Tubes as Class C Amplifiers", *I. R. E. Proc.* **23** (1935), 752-778.

3. E. L. Chaffee, "A Simplified Harmonic Analysis", *Rev. Sci. Instr.* **7** (1936), 38-42.

4. E. L. Chaffee, "The Operating Characteristics of Power Tubes". *Applied Physics*, **9** (1938), no. 6 June.

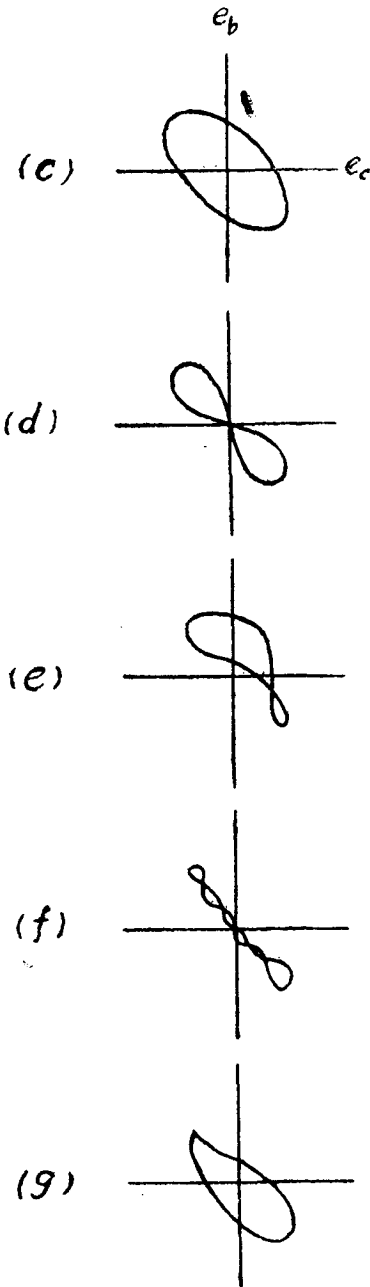


Fig. 1.

the same chosen end point. Hence, the plate efficiency is greatly reduced. In an oscillator, paths of operation like the ones shown in Fig. 1a and Fig. 1c are very rare. Fig. 1f shows a typical path of operation for a well designed Hartley oscillator and Fig. 1g shows a typical path for a Colpitts oscillator. With very careful design and adjustment, path of operation like those shown in Fig. 1b and Fig. 1d may be obtained. These are considered to be good approximations to the ideal straight line path. From the shape of the plate current characteristics and the schedule of harmonic analysis, it is evident that among the several paths shown in Fig. 1, the straight line path gives the highest plate efficiency.

Theoretically, an oscillator can be designed and adjusted so that its phase angle between  $e_g$  and  $e_p$  is as close to 180 degrees as possible. This, however, is not easy to do, especially when the oscillator is heavily loaded (which is always the case with a power oscillator). It can be shown<sup>5</sup> that Llewellyn's frequency stabilizing circuits<sup>6</sup> are also excellent circuits for phase compensation, but Llewellyn's design data are only good for oscillators with no load. When the oscillator is loaded, the design formulae should be modified<sup>5</sup> but in many cases exact compensation is impossible. In other words, the phase angle cannot be made exactly equal to 180 degrees and consequently the path of operation will have the general form of one or more open loops instead of a straight line. This amounts to saying that the efficiency of such an oscillator is comparable to that of a slightly detuned class C amplifier. It is no surprise, therefore, that the efficiency is much lower than a properly tuned amplifier.

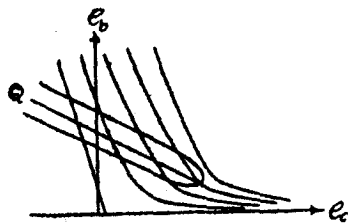


Fig. 2.

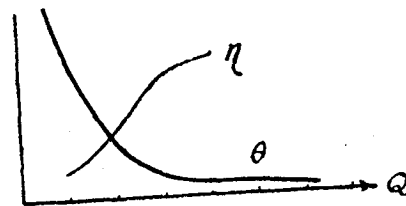


Fig. 3.

Fig. 3 shows some experimental results of the effect of loading a Colpitts oscillator upon the phase angle and the plate efficiency. The

5. Paper in preparation by same author.

6. Llewellyn, "Constant Frequency Oscillators", *I. R. E. Proc.*, **19** (1951), 2065-2080.

plate load is held constant at 6000 ohms and the load is increased so as to lower down the effective  $Q$ -factor of the oscillating circuit. Plotted against  $Q$  are the relative phase shift  $\theta$  (departure from 180 degrees) and the corresponding values of plate efficiency  $\eta$ . It can be seen that a sudden increase in the phase shift is always accompanied by a corresponding sharp decrease in plate efficiency. One can conclude, therefore, that unless proper phase compensating circuits are employed, the phase angle is in general not 180 degrees and therefore the efficiency would be low. The simplest method of measuring this phase angle is from the path of operation itself.<sup>7</sup> It is shown in another paper that if the net area of the loops of the path is equal to zero, the phase angle is 180 degrees. Loops next to one another have opposite signs when areas are measured. For instance, Fig. 1d is a symmetrical figure of eight, the net area is zero and the phase angle is correct. A cathode ray oscilloscope, when connected so that it reads  $e_p$  and  $e_s$ , is the best tuning indicator for an oscillator. A d.c. milliammeter placed in the plate circuit of an amplifier serves as an excellent tuning indicator, but this is not necessarily true in the case of an oscillator. A "dip" indicates a minimum d.c. power input but it does not give sufficient information regarding the output and the efficiency of the oscillator. In other words, a "dip" of the d.c. milliammeter in the plate circuit of an oscillator does not necessarily indicate proper or desirable adjustment. The cathode ray tube gives the whole picture of the path of operation and is, therefore, a much better indicator.

### 3. EFFECT OF HARMONICS

It is almost needless to point out that the output of an oscillator is more likely to have more harmonic content than a tuned amplifier. This is especially true in circuits where no by-pass capacitor is provided for the harmonic currents such as a Hartley oscillator. The result is that the path of operation is usually badly distorted. Even in a tuned-plate-tuned-grid circuit where the grid voltage is usually free from harmonics, the plate voltage has a considerable amount of harmonic content when the

7. See another paper by the author, "Measurement of Phase Angle between Fundamental Components of Two Non-sinusoidal Waves."

oscillator is loaded. Let us proceed to demonstrate the effect of such harmonics upon the shape of path of operation. For the sake of simplicity, let us assume that the grid voltage is free from harmonics and that the plate voltage has some considerable second harmonic content. We have then,

$$e_g = E_g \cos \omega t, \quad (4)$$

$$e_p = E_{p1} \cos (\omega t + \alpha_1) + E_{p2} \cos (2\omega t + \alpha_2). \quad (5)$$

Let 
$$x = \cos \omega t = e_g/E_g \quad (6)$$

and 
$$y = e_p.$$

Substituting (6) in (4) and (5), eliminating  $t$ , we have

$$y = a + bx + cx^2 \pm \sqrt{1-x^2}(A + Bx), \quad (7)$$

where

$$a = -E_{p2} \cos \alpha_2, \quad b = E_{p1} \cos \alpha_1, \quad c = 2E_{p2} \cos \alpha_2,$$

$$A = E_{p1} \sin \alpha_1, \quad B = 2E_{p2} \sin \alpha_2.$$

The path of operation is given by equation (7). There are three points at which  $y$  is single-valued. These are

$$x = \pm 1,$$

$$x = -A/B = \frac{-E_{p1} \sin \alpha_1}{2E_{p2} \sin \alpha_2}.$$

This indicates that the path of operation has only two loops and  $x = -A/B$  is the cross point. When the circuit is tuned, the coefficients of the various terms vary and the path changes from one form to another. An examination of equation (7) shows that the last term is responsible for the existence of open loops while the general shape of the path follows that of a parabola given by the first three terms. If the coefficient  $c$  is zero, the general shape will be that of a straight line.

It has been pointed out by Sarbacher<sup>8</sup> that if the path of operation departs from a straight line and if it follows a curve concave upward, the

8. R.I. Sarbacher, "Power Tube Performance in Class C Amplifiers and Frequency Multipliers as Influenced by Harmonic Voltage", *I.R.E. Proc.* **31** (1943), 607-625.

plate efficiency will be higher than when the path is a straight line. This means that the coefficient  $c$  should be positive and that  $a_2$  should be either in the first or in the fourth quadrant. The coefficient  $b$  is, of course, negative. This requires that the amplitude of the second harmonic voltage be opposite in sign to that of the fundamental during the power stroke of the path of operation. An examination of equations (2) and (3) shows that to meet this requirement,  $I_{p2m}$  must be negative. This is impossible, because an examination of the shape of the plate current characteristics reveals that  $i_5 + 1.73i_6$  can never be greater than  $i_1 + 1.73i_2 + i_3$ . In other words, we are in no position to expect that the harmonics generated in the oscillator might improve the path of operation. It always makes the path worse. This is illustrated in Fig. 1e which is something very common. If we put one or more harmonic terms in equation (5), the effect will be to increase more number of loops and the general shape of the path will not be any better.

It can be concluded, therefore, that the harmonic generation only "steals" the d.c. input power and produces effect more harmful than good, its sole contribution is to reduce the plate efficiency.

#### 4. DIFFICULTY OF PROPER ADJUSTMENT

The adjustment of a Class C amplifier is as straight-forward as its design. The design consists of the proper choice of two operating points, the quiescent point and the end-point of the path of operation, the former being determined by the plate supply voltage  $E_{bb}$  and the grid bias voltage  $E_{cc}$  and the latter being determined by the load  $R_b$  and the a.c. driving voltage  $E_g$ . These four variables are independent of each other and therefore adjustment is easily made. Once the correct values of  $E_{bb}$ ,  $E_{cc}$ ,  $R_b$  and  $E_g$  are used, the only adjustment is to tune the plate circuit to resonance for a straight line path of operation. For an average power triode, the grid bias voltage to be used for optimum operation is approximately given by<sup>9</sup>

$$E_{cc} = -1.75 E_{bb}/\mu. \quad (8)$$

All these adjustments can be easily made independently.

9. R. I. Sarbacher. *Hyper- and ultra-frequency Engineering*, p. 506, 1943 Edition.

In a power oscillator, however, things are not so rosy. In the first place, we cannot use a battery bias  $E_{cc}$ . If so, oscillation can never be started, since the tube is biased at 1.75 times the cutoff bias. One has to use a grid leak resistor the d.c. voltage across which serves as grid bias. The d.c. grid current depends on the shape of the path of operation which in turn depends upon the bias voltage. By increasing the resistance of the grid resistor, the bias voltage can be increased, but the relation is far from being linear. After the resistance has been increased to a large value, further increase usually results in little increase in bias voltage because the average grid current decreases when the negative bias is increased. The author's experience has been that an attempt of realizing the condition given in equation (8) by increasing the grid leak resistance almost always results in intermittent oscillation before the desired point is reached. This is especially true when the oscillator is heavily loaded. A re-adjustment of the excitation ratio of the oscillator may satisfy equation (8), but this changes the whole design. In conclusion, to design a good oscillator, one should not stick to the choice of proper operating points for an amplifier. These may be good on paper, but may not be feasible in laboratory.

It seems that for a given excitation ratio and load resistance, there is an optimum value of grid leak resistance to be used. This has been proved to be true both theoretically and experimentally. The results will be presented in another paper now in preparation.

## 5. CONCLUSIONS

This paper has presented, in part, the following points:

- (1) The efficiency of a power oscillator is inherently lower than that of a power amplifier, not only because it is self-driven but chiefly because the path of operation is not a straight line.
- (2) The phase angle is usually not 180 degrees, this results in an open loop for the path and hence reduces the efficiency.
- (3) The harmonic content present is always rich, the effect is to distort the path in such a way as to reduce the efficiency still further.

- (4) The grid bias is not an independent adjustment. It is usually difficult to choose the same operating point for the oscillator as that used for an amplifier.
- (5) The best tuning indicator for an oscillator is a cathode ray oscilloscope on the screen of which the path of operation can be directly seen.
- (6) With phase compensating circuits properly adjusted, the performance of an oscillator may approach that of an amplifier. This is true only when the path is approximately a straight line.
- (7) Any attempt in improving the shape of the path of operation to make it more like a straight line, or what is even better, to make it a curve concave upward, would improve the efficiency.

## 中 文 提 要

### 强 力 振 盪 器 之 板 極 效 率

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普通設計強力振盪器時，每忽略真空管工作路之重要性。本文指出相角及諧波對於工作路圖之影響以解釋何以實際上强力振盪器之效率，每較設計時所預測者較低。本文並述及增加振盪器板極效率之各種方法。