Proceedings

of the

Radio Club of America

Incorporated

November, 1933

Volume 10, No. 11

RADIO CLUB OF AMERICA, Inc.
11 West 42nd Street + + New York City

PROCEEDINGS
of the
RADIO CLUB OF AMERICA

Vol. 10 NOVEMBER, 1933 No. 11

CORRELATION OF THEORETICAL AND EXPERIMENTAL DATA ON CLASS C OPERATION OF RADIO FREQUENCY AMPLIFIERS†

By R. J. Davis and W. J. Cahill*

THE post-war decade witnessed the initial development of thermionic tubes of large power capacity for use in radio transmitters. The first years were necessarily spent in design improvements in the tubes themselves with principal emphasis upon large radio-frequency power output. The operating efficiency of the tube circuits, and the optimum cascading of the successive amplifier stages were usually treated as of secondary importance. The opening up of transmitter manufacture as a competitive industry, and the development of plate structures permitting considerably greater anode dissipation than the older types, has forced the question of tube and circuit efficiency into a position of primary importance in transmitter design, especially with reference to Class C operation with very high positive grid swings. While limitations due to the necessity of modulation fidelity prevent the full exploitation of these new developments in broadcast and telephonic transmission generally, code transmitters can be designed today having overall efficiencies from 20 to 25% greater than those in common use only a few years ago. It is with this type of circuit that the present paper is concerned.

Our work has not progressed to the point where complete data can be presented, but the preliminary computations will be described and illustrated with curves, a complete method of attack outlined, and a brief critique attémpted of other work in the field.

It is essential that complete static characteristics of the tube considered be at hand. To get these data in the region of positive grid swing is difficult on account of the emission of secondary electrons from the grid at high positive potentials. It is believed that on account of the short period of time during which high grid current passes in a r-f. cycle under Class C operation, this effect is small for all tubes except the high power water-cooled types. In order to avoid secondary emission when taking data, the grid must be placed at the desired positive potential just long enough for an oscillograph element to record the swing of current. By utilizing several elements, the instantaneous values of plate voltage and current, as well as grid voltage and current may be read on the same film. A detailed technique for this procedure has been given by Kozanowski and Mouromtseff[1]. The desirability of simultaneous records is evidenced by the fact that all practicable plate and grid voltage supplies will show considerable regulation when called on to supply the increment of current involved in switching the grid from zero volts to a high positive value. It is also necessary to allow the grid to retain its positive potential long enough to permit all transients in the voltage supply circuits to die down. Kozanowski and Mouromtseff have covered these factors very well in their technique.

Assuming that a satisfactory set of characteristic curves are at hand, the next step is to compute data following the method of Prince and Vogdes[2] which results in an ensemble of optimum conditions illustrated in Fig. 1. The details of the computations for *one* point on *one* curve are given in the appendix. It should be emphasized that the efficiencies given here refer simply to the ratio of r-f. power available to the input to the tube, taking account of both grid and plate losses, but without consideration of the transfer of fundamental frequency energy into a given plate tank impedance. To solve this problem, we have recourse to a procedure similar to that described by Fay[3]. Unfortunately, the method of Fay is open to considerable error when applied to Class C operation over angles of 50-60°, because of the fluctuation of the cut-off voltage with the instantaneous plate voltage. The method may be followed, however, provided the assumed data include the *angle of operation* as well as the *maximum positive grid swing*. This means in turn that the maximum grid swing must be adjusted to the value corresponding to the point selected by varying the excitation received from the preceding tube. We may now determine the value of plate impedance which will give maximum power out-

†*Presented before the Radio Club of America, October* 11, 1933.
**Hygrade Sylvania Corp.*

put at the fundamental frequency by utilizing Equation (12) of Fay's article, viz:

$$R_o = \frac{r_p}{K} \quad \ldots\ldots (1)$$

K is defined by the equation $K = \frac{\text{I fundamental max.}}{I_p \text{ max.}}$

K is a numerical factor uniquely determined by the angle of operation, r_p is the plate resistance of the tube at the point where I_p max. flows, and R_o is the equivalent resistance of the plate tank when tuned to resonance with the fundamental frequency. Referring to Fig. 2, we get a reasonable approximation to r_p by taking

$$r_p = \left(\frac{\Delta E_p}{\Delta I_p}\right)_{E_c = 300} = 6400^{w} \quad \ldots\ldots (2)\ \&\ (3)$$

$$R_o = \frac{6400}{.35} = 18000^{w} \quad \ldots\ldots (4)$$

Going back to our tube conditions, we find e_{pm}, the minimum plate voltage by Prince and Vogdes' criterion that $e_{g\ max}$. shall not be greater than 80 per cent of e_{pm}. Hence we know e_{pm}. The max. plate swing $=$ $E_b - e_{pm}$. $\frac{E_b - e_{pm}}{\sqrt{2}}$ gives the r.m.s. fundamental voltage impressed across the plate tank. The power output into the plate tank at fundamental frequency is given by the equation:

$$W_o = \frac{(E_b - e_{pm})^2}{2R_o} \quad \ldots\ldots (5)$$

This power will be delivered with the tube operating at maximum efficiency for its assumed output. The result comes out

$$W_o = \frac{(15000)^2}{(2 \times 18000)} = 63 \text{ watts} \quad \ldots\ldots (6)$$

This does not agree with the value calculated further on, because the value of r_p picked off the extrapolated $i_p - e_g$ curves is subject to considerable error. More exact numerical check of the above analysis follows:

$$E_b - e_{pm} = 2000 - 500 = 1500 \text{ volts} \quad \ldots\ldots (7)$$

$$\frac{E_b - e_{pm}}{\sqrt{2}} = 1060 \text{ volts r. m. s.} \quad \ldots\ldots (8)$$

$$W_o = \frac{E_b - e_{pm}}{2} KI_p \quad \ldots\ldots (9)$$

(I_p max $= .576$ amp.)

$$W_o = (750)\ (.35)\ (.576) = 152 \text{ watts} \ldots (9a)$$

The actual measured power in the antenna for two tubes in parallel was 306 watts. Losses in the tank and antenna tuning circuit were estimated at 15.0 watts per tube giving a total output per tube of 168 watts. The difference in the measured and calculated powers is 10%, and is probably due to an incorrect value of the constant K, as this is sensitive to changes in the assumed shape of the tip of the plate current curve. The value of K used here is the value given by Fay for a 3/2-power curve. If the shape of the plate current curve is taken as slightly flattened (probably a closer approximation on account of filament saturation), the value of K for 60 deg. operation comes out to be about .37. Substituting this in the above equation, we get

$$W_o = (750)\ (.37)\ (.576) = 160 \text{ watts} \ldots (10)$$

This gives a closer check.

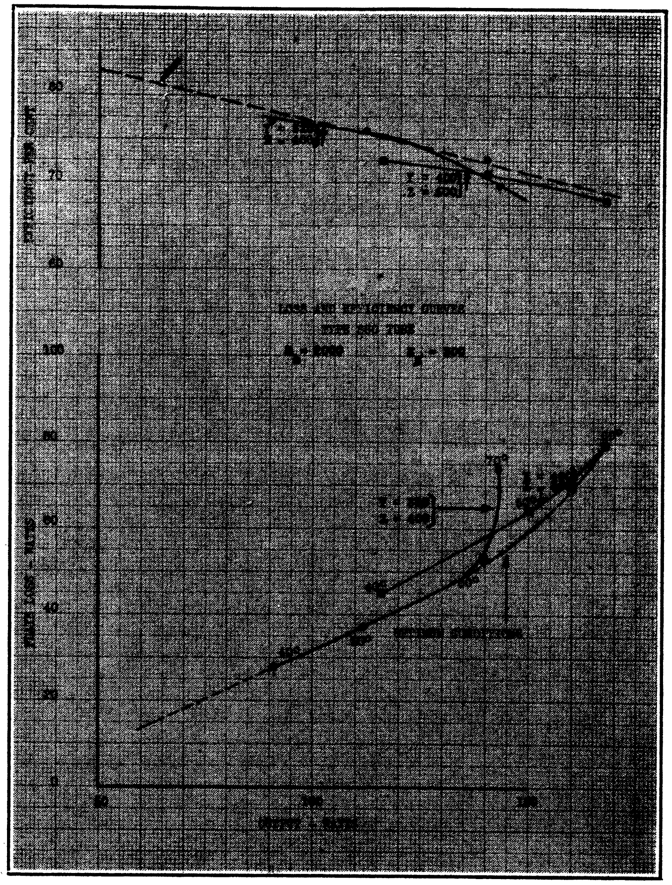

Fig. 1—Loss and Efficiency Curves.

In designing the plate circuit, the values of L and C are usually chosen with a primary view to stability. It is customary to assume a ratio of K.V.A./Watts in the amplifier tank circuit of about 20/1 to 30/1. This is in accordance with ideas developed in Prince and Vogdes' book which show that this ratio should be at least 12.6/1 for stable operation. The theoretical minimum is usually doubled to allow a factor of safety. A value of C is assumed, the circulating current through it at a given frequency determined with an r.m.s. voltage $\frac{E_b - e_{pm}}{\sqrt{2}}$ across it, and the value of R necessary to dissipate the power output with this circulating current through it found. L is determined from tuning considerations. The value of $\frac{L}{CR}$ is then computed and compared with the value of R_o obtained from the equation:

$$\frac{(KI_p)^2 R_o}{2} = 152 \quad \ldots\ldots (11)$$

$$K = \frac{I_1}{I_p} = \frac{\text{Peak Fund Current}}{\text{Peak Plate Current}}$$

$$R_o = \frac{152 \times 2}{(.35)^2\ (.576)^2} = 7500^{w} \quad \ldots\ldots (11a)$$

If the value of $\frac{L}{CR}$ differs markedly from this, a new value of C is selected, and the computation repeated until fair agreement is obtained.

The constants on the tank used in the experimental work are known, so that it is possible to check this

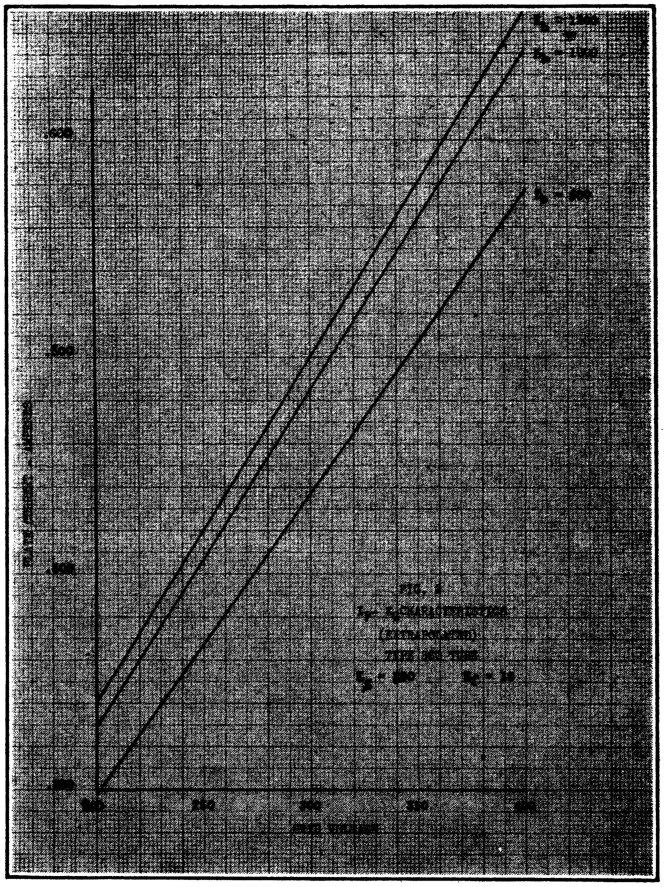

Fig. 2.

theory also. The measurement was made at a frequency of 2400 kilocycles/sec. The low frequency L of the tank by computation was 30 microhenrys. The C necessary to tune this to 2400 k.c. is 148 mmf. Of this, 92 mmf. was in the tank condenser, and 56 mmf. in the coil and circuit wiring as distributed capacity. With an r. m. s. voltage of $\frac{2000 - 500}{\sqrt{2}}$ or 1060 volts across the tank, the capacity current will be

$$I_c = \frac{1060}{X_c} = \frac{1060}{450} = 2.35 \text{ amp.} \quad (12)$$

In order to dissipate 168 watts, this current must traverse an equivalent resistance R given by the equation:

$$(2.35)^2 R = 168 \quad (13)$$

$$R = 30.2 \text{ ohms} \quad (13a)$$

This R includes the resistance of the tank coil itself together with the resistance reflected into the tank from the antenna circuit. The equivalent resistance of the tank R_o at fundamental frequency is then given by the equation

$$R_o = \frac{L}{CR} = \frac{30 \times 10^{-6}}{148 \times 10^{-12} \times 30.2} = 6700 \text{ ohms} \quad (14)$$

This is in fair agreement with the value (7500 ohms) deduced in equation (11a) above.

While the foregoing analysis may seem laborious, it can be attacked systematically, and the optimum values found very quickly. It should be noticed, furthermore, that the data so obtained are of use in designing circuits at any frequency and furnish a record of permanent value for the engineering files.

ADDENDUM

It should be noted that the power output of a tube computed by the method of Prince and Vogdes includes the *total* power available for transfer into a load, i.e. fundamental power and harmonic power. Fay's procedure leads to a value of *fundamental* power only. We should expect that the two values of computed power would differ, therefore by an amount equal to the *harmonic* power. For small angle Class C operation, this harmonic power is very small, so that close correlation between the available power outputs computed by the two methods should exist. The method of power measurement in the experimental work did not permit a sharp discrimination against the harmonic frequency power, so that part of the discrepancy between the measured and computed values may be explained as due to this fact.

REFERENCES

[1] **Kozanowski and Mouromtseff: "Vacuum Tube Characteristics in the Positive Grid Region: Proc. I. R. E., August, 1933; p. 1082.**

[2] **Prince and Vogdes: "Vacuum Tubes as Oscillation Generators": G. E. Company, July, 1929.**

[3] **C. E. Fay: "Operation of Vacuum Tubes as Class B and Class C Amplifiers": Proc. I. R. E. March, 1932; p. 548.**

APPENDIX

Tube: 860
60 deg. operation

D. C. plate volts X = 2000
Max. grid volts Y = 400
Min. plate volts = 500

		0°	10°	20°	30°	40°	50°	60°
A	1-cos θ	0	.0152	.0603	.1340	.2340	.3572	.5000
B	(X-Z) (1—cos θ)	0	22.8	90.5	201.0	351.0	536.0	750.0
C	e_p	500	522.8	590.5	701.0	851.0	1036.0	1250.0
D	e_p/u	60	60	60	60	65	65	65
F	Y plus e_p/u	460	460	460	460	460	460	460
G	1-cos θ	0	.015	.060	.134	.234	.357	.500
H	Max. grid swing (G)	—	—	7650	3440	1990	1300	930
J	A-C comp. of E_g	—	—	5420	2440	1410	920	660
K	Bias	—	—	—	3040	1590	900	530
L	1-cos θ	0	.015	.060	.134	.234	.357	.500
M	G (1-cos θ)	0	14	56	125	218	332	465
N	e_g	400	386	344	275	182	68	—65
P	i_p	.576	.560	.525	.440	.290	.124	0
Q	i_g	.082	.080	.070	.043	.028	.012	0
R	Plate loss	288	295	310	310	246	129	0
S	Grid Loss	32*	32	21	11	5		

$I_p = .124$
$I_g = .015$
Grid Loss = 4 watts
$R_g = 35{,}400^{w}$
R_g loss = 8 watts
Total grid loss = 12 watts

Plate loss = 80 watts
Input = 248
Output = 168
Efficiency = 67.6%