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by

C. Brunkhorst

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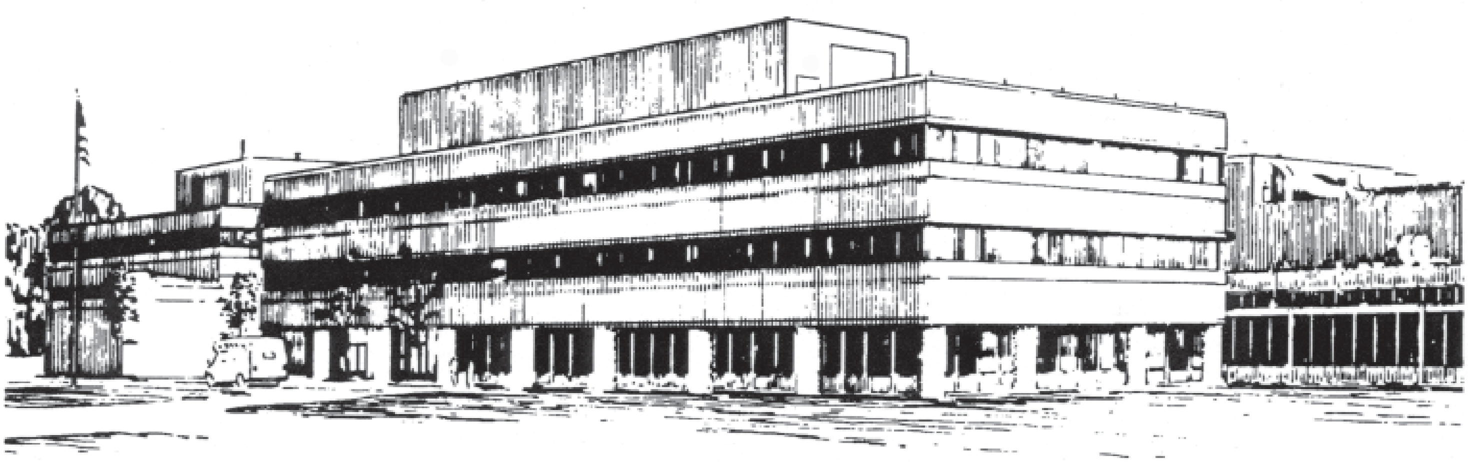

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Models for Automated Tube Performance Calculations

C. Brunkhorst, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, New Jersey, 08543*

Abstract-- **High power RF systems, as typically used in fusion research devices, utilize vacuum tubes. Evaluation of vacuum tube performance involves data taken from tube operating curves. The acquisition of data from such graphical sources is a tedious process. A simple modeling method is presented that will provide values of tube currents for a given set of element voltages. These models may be used as subroutines in iterative solutions of amplifier operating conditions for a specific loading impedance.**

I. Introduction

Chaffee analysis has long been used for the evaluation of amplifier operating conditions. This technique uses tube currents and voltages sampled at regular intervals during the RF cycle to provide a piecewise linear approximation of the currents over a 90 degree portion of the cycle. Tube current curves are used to obtain the data at the sampling points. The graphical nature of this data is a detriment to the full utilization of Chaffee analysis. As an example, it may be desired to obtain results for an amplifier operating at a specific plate load impedance. However, load impedance is found as a result of the analysis, so an iterative approach must be used. The need to obtain input data from tube curves for each iteration makes this impractical. The modeling method presented here removes this impediment.

II. The Method

Tube curves are published for either grounded grid or grounded cathode operation. An example will be shown using grounded grid curves for a typical tetrode (Fig. 1).

The Y-axis is cathode to grid voltage (*Vcg*), and the X-axis is plate to grid voltage (*Vpg*) in kV. Each curve consists of the locus of points for a constant value of the current in question, plate grid and screen in the case of a tetrode. The curves are given for a range of discrete values of current.

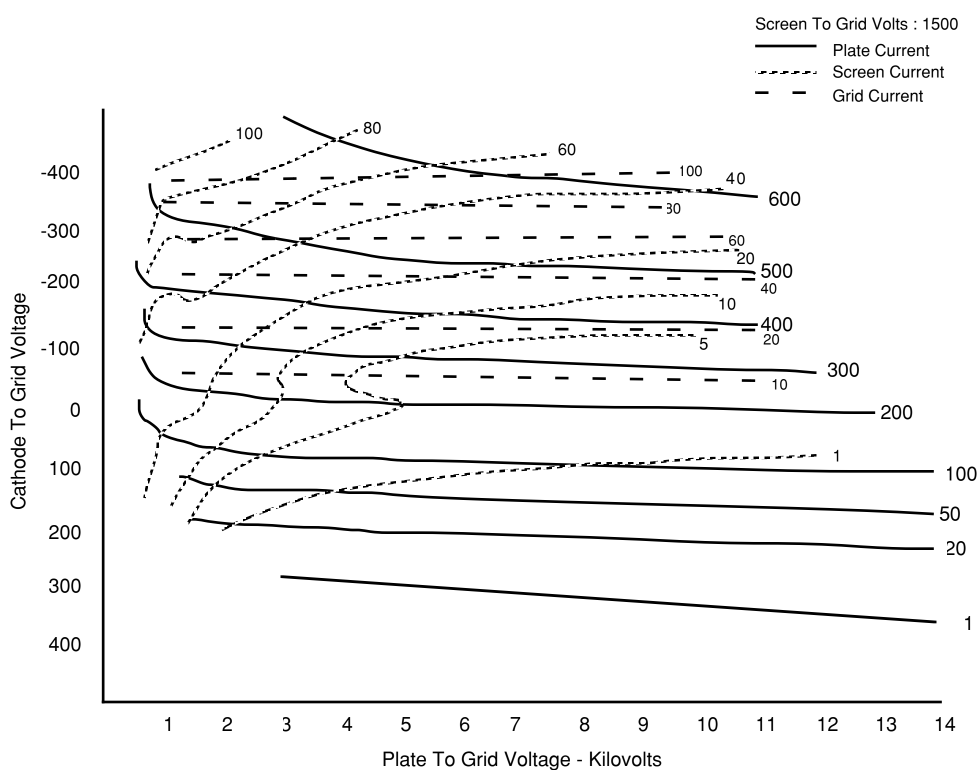

Figure 1
Constant current tube curves for a typical tetrode.

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The problem is: given values of *Vcg* and *Vpg*, what will the current be for a particular tube element? At any arbitrary *Vpg*, each constant current curve will be found at a particular *Vcg*. In this example, data was taken for plate current, (*Ip*) at *Vpg* = 10 kV, and the results are shown in table I.

Table I

Vcg	I*p*
340	1
230	20
170	50
110	100
10	200
-60	300
-140	400
-220	500
-360	600

This can be plotted as current vs. voltage, and a polynomial curve fit can be performed. A plot of the data from table I, and the resulting polynomial curve fit is shown in Fig. 2.

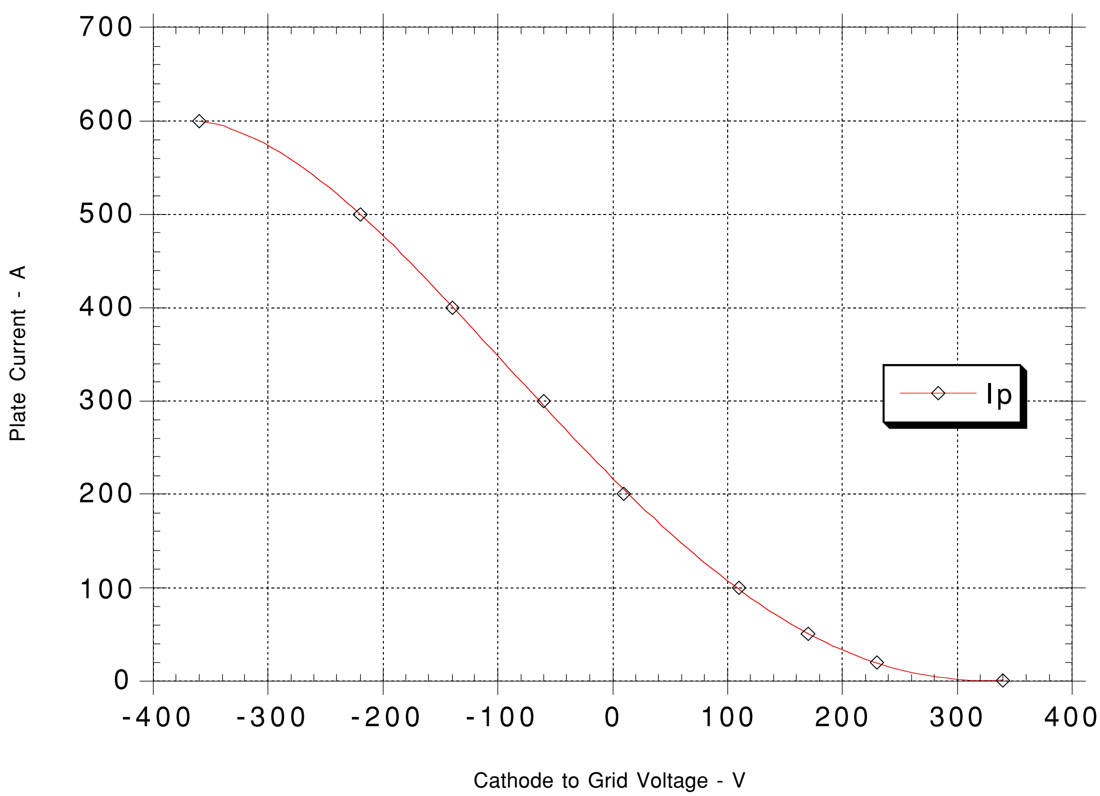

Figure 2

Plate current vs. cathode to grid voltage at 10 kV plate voltage, with a plot of the polynomial curve fit for the data in table II.

The order of the polynomial is chosen by trial and error, to provide the best fit to the data points. In the example, a fourth order polynomial results in a close match to the data. For this particular *Vpg*, we now have an equation that will provide the value of the plate current for any *Vcg*:

$$Ip = M0 + M1 * Vcg + M2 * Vcg^2 + M3 * Vcg^3 .... \quad (1)$$

At this point, some of the limitations of this approach must be mentioned. The goal is to reproduce the data contained in the original tube curve. It is therefore important to restrict the input data to the range of the values used in the curve fit. The polynomial can not be used to extrapolate behavior beyond this range. The curve fit will also give non-zero values of *Ip* for *Vcg* below cut off. A cut off limit is defined, and *Ip* set to zero if *Vcg* exceeds this limit. In this example, the 1 A plate current curve may be chosen as the cut off limit. Thus, for this example, *Ip* is set to 0 when:

$$Vcg \ > \ (7.14 * Vp \ + \ 269) \quad (2)$$

Having created an equation for *Ip*, this process can be repeated at regular intervals of *Vpg*, ΔVp. Equations now exist for *Ip* as a function of *Vcg* at multiples of ΔVp. The tube model consists of the set of polynomial coefficients at intervals of *Vpg* as shown in table II.

Table II

Vpg	*M0*	*M1*	*M2*	*M3*	*M4*
1	149.9	-1.110	.002932	1.453e-05	1.539e-08
2	171.4	-1.124	.0009835	4.051e-06	1.088e-09
3	186.4	-1.192	.0007355	4.851e-06	3.850e-09
4	192.7	-1.157	.0008050	3.146e-06	1.996e-10
5	195.2	-1.174	.0009574	3.055e-06	-1.050e-09
6	199.5	-1.184	.0009725	3.041e-06	-1.406e-09
7	201.0	-1.209	.001003	3.183e-06	-1.605e-09
8	205.8	-1.203	.001003	3.058e-06	-1.962e-09
9	213.5	-1.206	.0006653	3.110e-06	8.492e-10
10	214.9	-1.208	.0007318	3.006e-06	3.094e-10

To find *Ip* for a particular point, (*Vpg, Vcg*), Ip is calculated with the equations for 2 adjacent values of *Vpg* from table II:

$$V1 = \text{Integer Value}(Vpg / \Delta Vp) * \Delta Vp \quad (3)$$
$$V2 = Vp1 + \Delta Vp \quad (4)$$

Tube curves don t always extend to the maximum *Vpg* that may actually be used. It is reasonable to assume that the curves continue in a linear fashion. The curves may be extrapolated using the data at the highest values of *Vpg*. So if $Vpg \geq 10$, then:

$$V1 = 9 \quad (5)$$
$$V2 = 10 \quad (6)$$

Plate currents are now calculated using the equations from table II at *Vpg = V1* and *Vpg = V2*:

$$Ip1 \ = \ \mathrm{f}(\ V1,\ Vcg) \quad (7)$$

$$Ip2 \ = \ \mathrm{f}(\ V2,\ Vcg) \quad (8)$$

The final result is found by interpolation:

$$Ip \ = (\ (Vpg - V1)/ \ \Delta Vp \ * \ (Ip2 - Ip1) \ ) \ + \ Ip1 \quad (9)$$

Tube curves are created for a specific screen to grid voltage (*Vsg*). The model may be used for other values of *Vsg* in the following manner:

$$K = Vsg / Vo \quad (10)$$

Where *Vo* is the nominal screen to grid voltage for the tube curve used in the model. *K* is used to transform *Vpg* and *Vcg*:

$$Vpg' = Vpg / K \quad (11)$$
$$Vcg' = Vcg / K \quad (12)$$

Vpg' and Vcg' are now used as input data for the model, and the current Ip' is computed. The plate current is now calculated from Ip':

$$I\mathrm{p} \ = \ I\mathrm{p}' \ * \ K^{1.5} \quad (13)$$

The same method may be used to obtain screen and grid currents. Plate and grid currents are obtained with good accuracy. Due to the usually convoluted nature of the constant current curves for the screen, the results are not as good as for plate and grid current.

III. Applications

It is a simple matter to employ tube models as subroutines in Chaffee analysis. The model is used to obtain plate, screen and grid current values every 15 degrees over one quarter of the RF cycle. From this data, DC and peak fundamental RF currents are calculated. From these currents power output, plate, grid and screen dissipation, and drive power may be calculated. A complete description of Chaffee analysis may be found in [1].

When Chaffee analysis is performed, the peak RF voltage applied to the cathode (or grid for the common cathode configuration), and the minimum instantaneous plate voltage are required input parameters. If these are chosen arbitrarily, desired output power and plate impedance can not be predicted accurately. An iterative approach can be used to predict tube behavior at specific loading and power levels. Given a desired output power (*Po*), and plate impedance, the plate swing can be calculated. The RF voltage applied to the cathode can be increased at each iteration by an amount, ΔVc, and the output power (*Px*) calculated. This is repeated until:

$$\mathrm{Sign}(\Delta Vc) * (Po - \ Px) \ < \ 0 \quad (14)$$

Then:

$$\Delta Vc = \Delta Vc * -0.5 \quad (15)$$

ANODE	22	kV
SCREEN	1000	V
BIAS	-500	V
IMPEDANCE	110	Ω
POWER	1800	kW

	Plate	Screen	Grid	Cathode	
Idc	104	4.0	5.6	113	A
I(f1)	181	7.7	10.6	199	A pk
Diss	478	4.0	1.0		KW

Efficiency	79	%
Z IN	3.6	Ω
P IN	71	KW

ANGLE	0	15	30	45	60	75	90	°
VP	22	16.9	12.1	7.9	4.8	2.8	2.1	KV
VCG	500	316	145	-2	-115	-186	-210	V
IP	0	0	69	212	340	409	425	A
IG2	0	0	0	0	7	24	34	A
IG1	0	0	0	1	18	31	37	A
IK	0	0	69	213	364	464	496	A

Figure 3
Output from Chaffee analysis for an Eimac 4CM2500KG tetrode, using a model as described in this paper.

The process is repeated until the difference between *Px* and *Po* is within the desired precision. Fig. 3 is a sample output from such a model for an Eimac 4CM2500KG tetrode.

The above process can be further iterated to obtain data for intervals of output power up to the point of saturation.

IV. Conclusion

This method has been used extensively at the Princeton Plasma Physics Laboratory and at the MIT Plasma Science Fusion Center. It has proven its worth as a design tool, and as an aid to the tuning and trouble shooting of RF systems.

References

[1] Eimac, Care and feeding of Power Grid Tubes. San Carlos, CA.

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