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NONLINEAR SIMULATION OF A TETRODE
VACUUM TUBE

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Nonlinear Simulation of a Tetrode Vacuum Tube

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Abstract

We have developed a variety of circuit models that may be used to simulate vacuum triodes and tetrodes in the extremes of nonlinear operation – from cutoff to saturation. These models, which run on Spectrum Software's Microcap-IV® (MC4) electronic circuit analysis program, have been used to analyze radiofrequency (rf) amplifiers and high-voltage pulse modulators.

In this preliminary report, we provide a single example of a high-power tetrode model and its use in a simple radio-frequency amplifier circuit. Within the next few months, we intend to produce a more exhaustive report that will provide a detailed explanation of the purpose of specific model elements, simulation of a variety of vacuum triodes and tetrodes, and additional circuit applications for these models.

Nonlinear Simulation of a Tetrode Vacuum Tube

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Introduction

Several members of our rf technology group are involved in the design and construction of high-power 2.8 MHz and 5.6 MHz rf buncher amplifiers¹. We are also designing a new (tetrode) version of an existing modulator that drives the mod-anode on the LANSCE² 805 MHz klystrons. Such projects benefit from electronic simulations on SPICE or similar software. The familiar linear models of vacuum tube circuits are not sufficient for our requirements. Therefore, we have developed several models of triodes and tetrodes which are capable of simulating highly nonlinear operation. These circuit models operate under Spectrum Software's Microcap IV³ application, which is based on UC Berkeley SPICE2G.

We have had requests for a description of this work, and plan to prepare a detailed report. Because that document will not be available in the short term, we are providing this brief preliminary report on a more timely basis.

¹ The buncher amplifier upgrade project is led by John Lyles, LANSCE-5, Los Alamos National Laboratory.

² 'LANSCE' is the acronym for 'Los Alamos Neutron Science Center'

³ Spectrum Software, 1021 S. Wolfe Road, Sunnyvale, CA 94086 Phone: (408)-738-4387

Simulation of the Thomson-CSF TH 537 Tetrode

We have developed several nonlinear equivalent circuits for the Thomson TH 537 tetrode. One example is shown below:

TH537 Tetrode Model

Figure 1. Basic TH 537 tetrode model. The elements labeled 'NF' are MC4 function sources.

Some elements (diodes 'Da', the 1 M Ω resistors) were introduced to ensure appropriate operation in 'cutoff' regions. Other elements (such as 'leaky' diode 'Dr') were required for stable operation of MC4. The diode .MODEL statements and the .DEFINE statements for the function current sources (Ig1, Ia, Ig2) appear on the following page.

Diode Model Statements:

```
.MODEL Da D (IS=10F RS=0 N=1 TT=0 CJO=0 VJ=1 M=500M EG=1.11 XTI=3
KF=0 AF=1 FC=500M BV=0 IBV=100P RL=1E19)
```

```
.MODEL Dr D (IS=10F RS=0 N=1 TT=0 CJO=0 VJ=1 M=500M EG=1.11 XTI=3
KF=0 AF=1 FC=500M BV=0 IBV=100P RL=1E6)
```

The three generators used to simulate grid and anode currents are MC4 function sources. The particular .DEFINE statements that describe each of the function sources (Ia, Ig2, and Ig1) are listed below. The desired nonlinearities are arbitrarily introduced as factors in the .DEFINE statements for anode, screen grid, and control grid perveance (Kp, K2, and K1).

Anode Current:

```
.DEFINE Ia Kp*(Egk+(Vg2/Mus)+(Va/Mup))^1.5
.DEFINE Kp 23030u*(1-exp(-Va/(600)))*(1-exp(-Vg2/150))
```

Screen Grid Current:

```
.DEFINE Ig2 k2*(Egk+Vg2/Mus)^1.5
.DEFINE k2 300u*(1+30*exp(-Va/1000))
```

Control Grid Current:

```
.DEFINE Ig1 k1*(Egk)^1.5
.DEFINE k1 8750u*(.15+.85*(1500/(750+Vg2)))
```

Voltage Definitions:

```
.DEFINE Egk (V(g)-V(k))
.DEFINE Va (V(a)-V(k))
.DEFINE Vg2 V(g2,k)
```

Mu Definitions:

```
.DEFINE Mup 200
.DEFINE Mus 5
```

The quantities Mup and Mus are, respectively, the μ 's associated with anode and screen grid.

Inter-electrode capacitances may be entered on the MC4 schematic as shown below.

TH537 interelectrode capacitances

Figure 2. Tetrode interelectrode capacitances. The tie-points represent the tetrode anode (A), control grid (G1), screen grid (G2) and cathode (K). Later (see Fig. 6), a 1 n Ω current-monitoring resistor will be connected between the anode (A) and the interelectrode capacitances.

On the following page, see simulated anode current characteristics and curves derived from manufacturer's published data.

Figure 3. TH 537 anode current characteristics. Top: simulated in MC4 model, bottom: Curves derived from Thomson's published data (with estimates at low anode voltage).

In Figure 3, note that the fit is better at higher anode currents than at operating points near cutoff. The region where greatest accuracy is required is taken into consideration as the model is being developed.

Screen grid characteristics

Figure 4. Simulated TH 537 screen grid characteristics. The values of screen current at anode voltages down to ~2 kV are in reasonable agreement with the manufacturer's published curves for this tetrode; values at zero anode voltage are guesses. With appropriate measurements, of course, these values could be determined.

Control grid characteristics

This model simulates the effect of screen voltage on control grid current. These effects can be seen in the following plot, where screen voltage is stepped from 750 V to 2000 V.

Figure 5. Simulated TH 537 control grid characteristics.

The following tetrode model is placed on the same MC4 schematic with the rf circuit elements. Note the 1 n Ω monitoring resistor 'ac' that has been inserted for measurement of the capacitive element of anode current.

Figure 6. The TH 537 vacuum tetrode model with ‘test’ power supplies and grounds removed.

See the next figure for the remainder of this MC4 ‘input file’ schematic.

Figure 7. Schematic of rf amplifier 'tied' to TH 537 model in Figure 6.

This radio-frequency amplifier is entered on the same MC4 schematic with the previous figure. They are connected together with 'tie points' corresponding with the tetrode anode (A), screen grid (G2), control grid (G1), and cathode (K). This procedure is not necessary, of course, but separation of the vacuum tube model from the rf amplifier circuitry tends to simplify interpretation of the schematic diagram.

Results of transient analysis follow.

Time Range	2u
Maximum Time Step	.1n
Number of Points	51
Temperature	27

						Auto Scale Ranges		
U	M	N	H	Y	P	H Expression	Y Expression	H Range
☐	☒	☐	☐	☐	2	T	v(Anode)	2u,0
☐	☐	☐	☐	☐	1	T	v(G1)	2u,0
☐	☐	☐	☐	☐		T	I(Rg1)	2u,0
☐	☐	☐	☐	☐	3	T	I(Ra)	2u,0
☐	☐	☐	☐	☐		T	sum(abs(I(Ra)*V(Ra)))	2u,0
☐	☐	☐	☐	☐		T	I(Rg2)	2u,0
☐	☐	☐	☐	☐		T	V(Scrn)	2u,0
☐	☐	☐	☐	☐	4	T	I(Ra)-I(ac)	2u,0
☐	☐	☐	☐	☐				
☐	☐	☐	☐	☐				
☐	☐	☐	☐	☐				
								Y Range
								Fmt
								5.3
								5.3
								5.3
								5.3
								5.3
								5.3
								5.3
								5.3
								5.3

Figure 8. The MC4 Transient Analysis Limits table for circuit shown in figs. 6 and 7. The four selections selected under column 'P' are plotted below in Figure 9.

Figure 9. MC4 transient analysis results from circuit in figs. 6 & 7. Traces, from top to bottom, are control grid voltage, anode voltage, total anode current (including the capacitive component), and anode current minus the capacitive component. Time scale is 0 - 2 μ S.

The transient analysis below includes a calculation of anode energy dissipation.

Figure 10. MC4 plots of anode current and anode energy dissipation. Time scale is 0 - 2 μ s. (Refer to circuits shown in figs. 6 and 7.)

Summary

We have described the nonlinear simulation of a TH 537 tetrode in an rf amplifier. The circuit analysis described in this report was performed using MicroCap IV® on a Power Computing 'Power Tower Pro 225®' computer, using Macintosh® operating system 7.6. On a benchmark MC4 file, this computer operates about 15 times faster than a Macintosh® Quadra 950. Increased speed on the Power Tower Pro 225® (or an equivalent machine) is significant, because typical amplifier transient simulations required almost an hour of Quadra 950 time. The MicroCap software is also available for personal computers using Windows® operating systems. Spectrum Software may be consulted for details.

It is not our purpose to present this particular topology as the most appropriate for vacuum tetrodes, or as optimum for the TH 537. We have, in fact, used several circuit models to simulate this particular tetrode. The model used depend upon the circuit requirements; in a specific circuit, one tetrode model will typically run with greater stability than another. Some models that perform well in d.c. analysis (where characteristic curves are generated as the model is under development) will not run in transient analysis once the completed tube model is 'plugged into' a simple pulsed or rf circuit. Pivot errors are not uncommon. The particular tetrode model presented here meets our current needs for a specific rf amplifier application; other design problems may require a model with different features.

In a future report, we plan to provide details on how a variety of triode and tetrode vacuum tubes may be simulated for nonlinear operation. We intend to provide several examples of circuits which use these models.

Those with questions, comments, or advice on how we might improve these models are invited to contact the author:

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