COMMENTS ON "SPICE MODELS FOR VACUUM-TUBE AMPLIFIERS"*

In the above paper,[1] W. M. Leach, Jr., presented *PSpice* models for two types of tubes: the triode and the pentode. Work on the simulation of vacuum tubes with a SPICE-type electronic simulation program has already been undertaken,[2-7] and the purpose of our comments is to compare the different contributions.

The first attempt at modeling vacuum tubes in a SPICE-type software that we are aware of originated from Intusoft (San Pedro, CA) in 1989.[2] The triode model presented was based on a 3/2-power law, as in Leach.[1] The pentode models were simply derived using MOSFET transistors or cascoded triode models. Models for various tubes using these topologies were then included in the libraries of the ICAP/2 package from Intusoft. The models are still useful because they are completely Berkeley SPICE 2G compatible and can thus be used with virtually all SPICE simulators. They also run much faster than behavioral versions,[1, 4-7] albeit with less accuracy.

A few years later Broydé and Clavelier [4-6] from Excem (Maule, France) introduced more elaborate triode, beam tetrode, and pentode models for the ICAP/4 package from Intusoft. The implementation uses the analog behavioral capabilities (mathematical equations) of the SPICE 3B element and an if–then–else feature incorporated into IsSpice by Intusoft. Their triode model is valid under direct or reverse bias, and includes:

- A description of the control grid current under positive grid bias
- A description of the flattening of the I_A versus V_A curves as the reverse grid voltage is increased (reduction of the effective cathode area)
- A description of the high current thermoionic emission saturation
- A description of thermal effects in the filament.

This last feature is optional and may be used according to the level of accuracy desired. (It slows down the simulation significantly.) The electronic portion of the model requires 14 parameters. The heater model, if utilized, requires nine additional parameters.

The curves for a small generic triode (Figs. 1 and 2) provide a good example of the accuracy that may be obtained with this model. This model is far more precise and representative of actual tube performance than the extremely simplified version shown in Fig. 2 of Leach.[1]

The beam tetrote and pentode models of Broydé and Clavelier have 20 parameters and provide, in addition to the properties of the triode model:

- A description of the screen grid current
- A description of the disappearance of the virtual cathode at low V_A.

An example of the characteristics of a generic power pentode is given in Fig. 3. It does not have the sharp edges shown in Fig. 7 of Leach.[1] The number of model parameters provided allows an excellent match of virtually any type of screen grid tube with negligible secondary emission. A simulation of a MOS transistor–beam tetrode amplifier is shown in Fig. 4. This circuit was actually built and compared well with the simulation results.

The generic versions of the triode and pentode tube models are included in the Intusoft ICAP/4 SPICE model libraries.

More recently Rydel took over this work and created over 40 tube models[7,8] that match specific tube character-

* Manuscript received 1995 July 7.

[1] W. M. Leach, Jr., "SPICE Models for Vacuum-Tube Amplifiers," *J. Audio Eng. Soc.*, vol. 43, pp. 117–126 (1995 Mar.).

[2] L. G. Meares, "A Spice Model for a Vacuum Triode," *Intusoft Newsl.*, pp. 1–6 (1989 Feb.).

[3] S. Reynolds, "Vacuum Tube Models for PSpice Simulation," *Glass Audio*, vol. 5, no. 4, pp. 17–23 (1993).

[4] F. Broydé and E. Clavelier, "Modélisation et simulation des circuits à tubes avec IsSpice 3," *Electronique Radio Plans*, no. 553, pp. 69–73 (1993 Dec.).

[5] "Modeling Vacuum Tubes," *Intusoft Newsl.*, pp. 6–11 (1994 Feb.).

[6] "Modeling Vacuum Tubes, Part II," *Intusoft Newsl.*, pp. 7–11 (1994 Apr.).

[7] C. Rydel, "Simulation of Electron Tubes with Spice," presented at the 98th Convention of the Audio Engineering Society, *J. Audio Eng. Soc. (Abstracts)*, vol. 43, p. 395 (1995 May), preprint 3965.

[8] *Vacuum Tube Modeling Package*, vol. 1: *User's Guide*, Excem (1995 June).

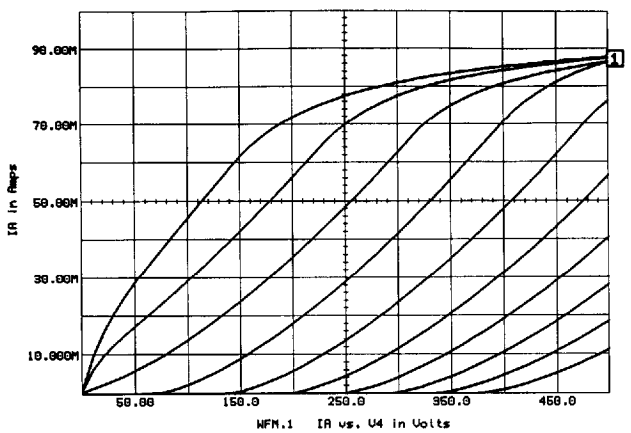

Fig. 1. Anode current of generic triode.

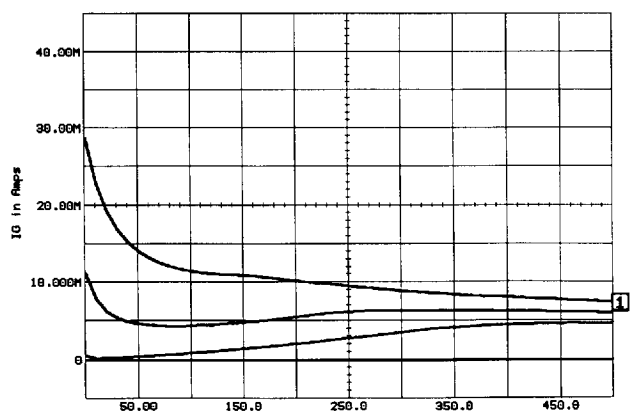

Fig. 2. Control grid current of generic triode.

istics relevant to audio engineering accurately, even though he used simpler models than Broydé and Clavelier. As far as we know, such models have never been published. Implementation of these models in typical tube circuits such as RIAA preamplifiers, Williamson amplifiers, and power supplies gives excellent results.

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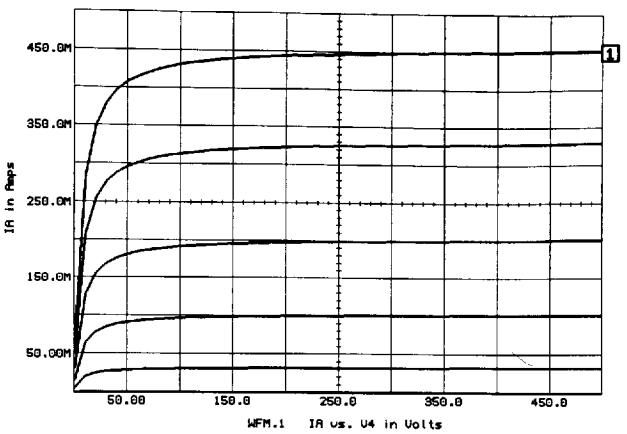

Fig. 3. Anode current of generic pentode.

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W. M. Leach Jr.'s paper[1] on electronic tube simulation has simultaneously raised my interest and triggered my questioning. To my knowledge, literature on the subject, if rather scarce, is recurrent.[2,3,5,6,10] For years, tubes had been confined both to a subjectivistic self-proclaimed golden-ears coterie and to a marketing set whose interest in the technique was limited and principally empirical, the aim being to reproduce and evaluate structures from the golden age of electronics. Dr. Leach's paper forcefully illustrates that tubes are not only still there, but can be the subject of mathematical developments, given simulation contexts. Doing so, he has reached his aim.

This being said, I will nevertheless express some reserve as to the general method of implementation used for modeling the tubes (similar to Reynolds[3]). Leach starts out with classical expressions, such as those given by the Langmuir–Child law, and then derives the ρ, g_m, μ, . . . parameters for a triode and a pentode. Curves cosmetically similar to those found in physics textbooks can be obtained by such a classical approach. However, they cannot in the least account for the distortion and nonlinearity phenomena affecting the tubes. Leach's method, it seems to me, overlooks phenomena which, however secondary, could alter the accuracy of simula-

[9] Manuscript received 1995 July 11.

[10] F. Broydé, E. Clavelier, D. Givord, and P. Vallet, "Discussion of the Relevance of Transfer Admittance and Some Trough Elastance Mesurement Results," *IEE Trans. EMC*, vol. 35, pp. 417–22 (1992).

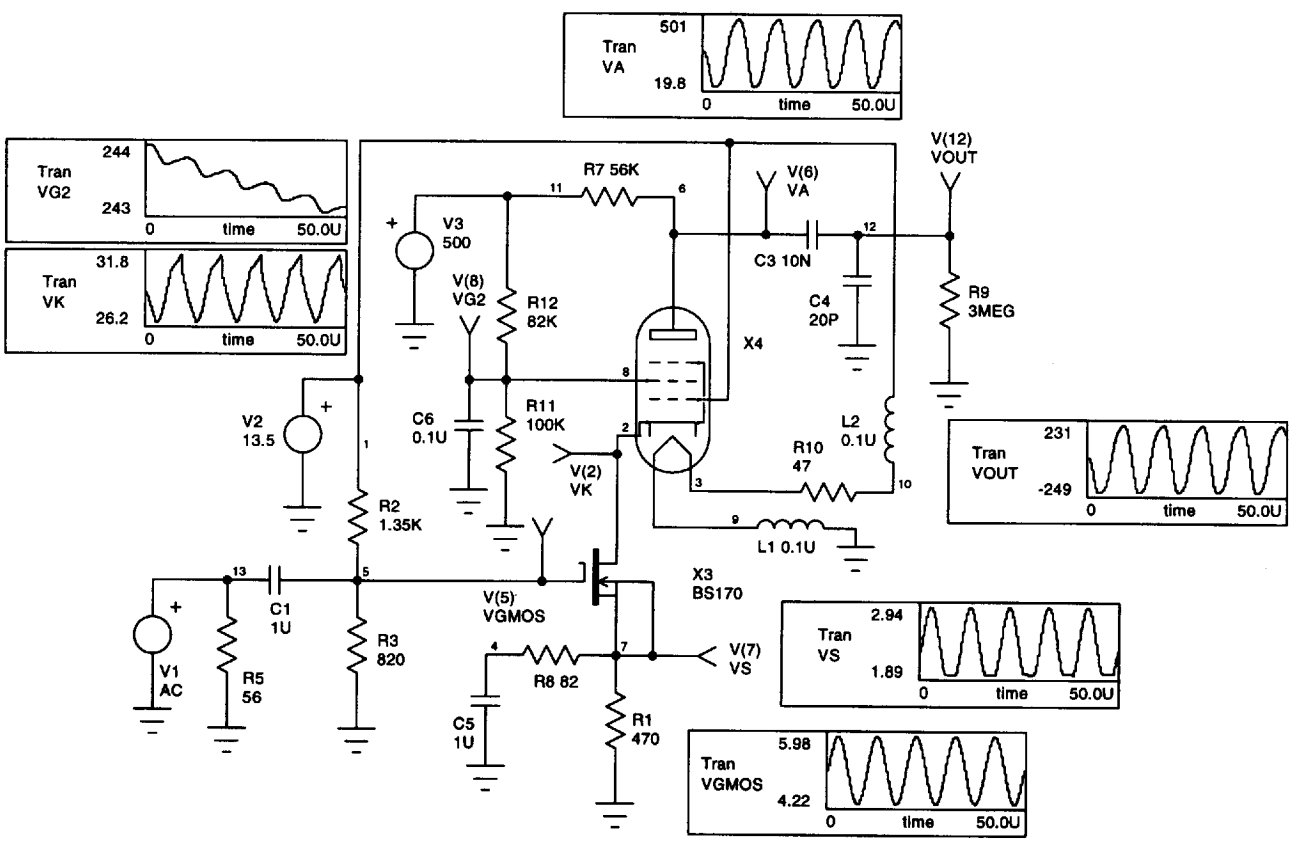

Fig. 4. Hydrid MOS transistor–pentode amplifier and simulation results obtained with ICAP/4.