Modeling Vacuum Tubes

In the February 1989 *Intusoft Newsletter*, Intusoft published one of the first vacuum diode/triode tube models using SPICE 2G syntax. The models, described in [1], used the polynomial features of IsSpice 1.41 to simulate the nonlinear V-I response. Since then electronic designers of audio and high voltage circuits who need electronic tubes have, until now, been requesting more "serious" tubes models. In order to satisfy the development requirements and evolution of high voltage amplifiers, as well as the need for better models, EXCEM, the Intusoft distributor in France, has developed much more advanced and accurate models. They are compatible with IsSpice3 and the new IsSpice4 simulators, which are based on Berkeley SPICE 3F.2.

Both specific and generic models, which can be modified by the user, are available. As an example, models for the 12AU7 triode and the EL9000 pentode are given. These components are used in some simple amplifiers. The plots obtained through simulation accurately describe the behavior of the tubes. Several other tube models are included on the newsletter floppy disk for subscribers. In this issue we will deal with the triode, leaving the pentode for the next newsletter.

A Realistic Triode Model

Until now, the Intusoft triode model used a fundamental law to describe the variation of the anode current (IA) with anode (VA) and grid voltage (VG):

$$I_a = K\left(V_g + \frac{V_a}{\mu}\right)^{1.5} \qquad \text{Eq.1}$$

where K is the perveance and μ is the amplification factor. With this law, the anode current is continuously increasing with anode voltage. Triode tube users know that such a law is not entirely realistic. With high currents (pulsed), or when the tube is "pumped", there is a saturation phenomenon such that the current value asymptotically reaches a maximum.

Table 1 shows the models for the 12AU7 triode, the generic triode, and the heater model. The generic triode, called TRIO1, contains equations using the IsSpice3 B element with its If-Then-Else syntax (IF expression <> expression THEN(?) expression ELSE (:) expression). TRIO1 describes the triode's electrical phenomena while the HEAT1 subcircuit describes the thermal phenomena for the filament and cathode. TRIO1 is

Table 1, Forward and reverse conditions are treated in the triode model, as well as saturation. The sample tube, a 12AU7A, is composed of the TRIO1 and heater subcircuits. The model for the heater gives a voltage, ISAT, that is an analog of the saturation current of the cathode. All tube models COPYRIGHT EXCEM, 1993.

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.SUBCKT T12AU7A1  1      2    3          4   5
*                       Anode Grid Cathode  F    F'
X1 1 2 3 10 TRIO1 {SFS=0.7 VBIG=-0.9 VBIA=-1.3 MU=17 RMU=0.5 VMU=-20
+ SFMU=1.6 K=827E-6 RK=0.08 VK=-20 SFK=1.6 SIGMAG=0.05 ALPHAG=5.2 SFG=3.5}
X2 4 5 10 HEAT1 {INOM=0.15 VNOM=6.3 LAMBDA=1 RCOOL=3 TCTE=10 TNOM=1150
+ INIT=1 W=2.045 ISAT=0.099}
C2 1 2 1.5P
C3 3 1 0.5P
C4 2 3 1.6P
C5 3 4 4P
C6 3 5 4P
.ENDS
*******************
.SUBCKT TRIO1    A  G  C ISAT
B1 15 0 V=V(G) - V(C) <  -1P ?
+ {K} * (1 + {RK} * (V(G) - V(C) / {VK})^{SFK}) / (1+(V(G) - V(C) / {VK})^{SFK}) : {K}
B2 16 0 V=V(G) - V(C) <  -1P ?  {MU} * (1+{RMU} * (V(G) - V(C) /
+ {VMU})^{SFMU}) / (1+(V(G) - V(C) / {VMU})^{SFMU}) : {MU}
B4 9 0 V = V(G) - V(C) - {VBIG} + (V(A,C) - {VBIA}) / (V(16) + 1U)
B6 10 0 V = V(9) > 0 ? V(15) * V(9)^1.5/(V(ISAT) + 1P) : 0
B7 12 0 V = V(10) < {SFS} ? V(10) * (V(ISAT) + 1P) :
+ (V(ISAT) + 1P) * ({SFS} + (V(10) - {SFS}) * {1-SFS} / ({1-2 * SFS} + V(10)))
B8 14 0 V = V(A) - V(C) > {VBIA + 0.1M} ? (V(A) - V(C) - {VBIA}) / {ALPHAG} : 2P
B9 28 0 V = V(G) - V(C) > {VBIG + 0.1M} ? V(14) > 1P ? ((V(G) - V(C) - {VBIG} +
+ {SIGMAG^(1/SFG)} * V(14)) / (V(G) - V(C) - {VBIG} + V(14)))^{SFG} : 0
B10 8 0 V = V(G) - V(C) < 0 ? V(28) * ((({VBIG+10U} + V(C) - V(G)) / {VBIG+10U}) : V(28)
B15 G C I = V(8) * V(12)
B17 A C I = (1 - V(8)) * V(12)
.ENDS
*******************
.SUBCKT HEAT1  F  F' ISAT
V1 F 4 0
R1 5 4 0.01
B1 5 F' V = V(7) > 0 ? I(V1) * ({VNOM / INOM - RCOOL} *
+ (1 + {LAMBDA} * (V(7) - 1)) + {RCOOL}) : I(V1) * {VNOM / INOM}
B2 6 0 V = (V(F) - V(F')) * I(V1) > 0 ? (V(F) - V(F')) * I(V1) / {VNOM * INOM} : 1
R2 6 7 1
C1 7 0 {TCTE} IC={INIT/100}
E1 13 0 7 0 {TNOM}
B3 ISAT 0 V = V(13) > 0 ?
+ {ISAT} * V(7)^2 * EXP({W/0.8417E-4} * (1 / {TNOM} - 1 / (V(13) + 1))) : {ISAT}
.ENDS
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See Table 2 for notes on the B elements and parameters

connected to the anode, grid, and cathode of the triode. A 4th node (node 10) receives the saturation current created by the HEAT1 subcircuit (the triode saturation current is determined by the cathode temperature).

It was interesting to model the differences in the concavities of the IA versus VA curves for different values of the grid voltage, which are not described with Eq.1. To take this effect into account, the model introduces correction factors to the K and μ coefficients when VG is very negative. These corrections appear in the TRIO1 subcircuit where B1 and B2 describe the

Table 2, The generic parameters for the triode and heater subcircuits reveal the tremendous versatility of the model.

The Triode Parameters Are:

SFS	Shape factor of the saturation law.
VBIG	Contact potential of the grid (the voltage above which current grid may start to flow).
VBIA	Contact potential of the anode.
MU	Amplification factor at slightly negative grid voltage.
RMU	Reduction factor for MU at very negative grid voltage.
VMU	Grid voltage for mid-range MU (negative).
SFMU	Shape factor for MU reduction law.
K	Perveance at slightly negative grid voltage.
RK	Perveance reduction factor at very negative grid voltage.
VK	Grid voltage for mid-range perveance (negative).
SFK	Shape factor for perveance reduction law.
SIGMAG	Effective cross-section of the grid relative to the anode.
ALPHAG	Grid current amplification factor.
SFG	Shape factor of the grid current law.

Model Notes: B7 contains an arbitrary saturation law modeled by the shape factor SFS to match the available data. SFS should be between 0 and 1, and the lower SFS, the sloppier the saturation law. V(15) is the effective perveance. V(16) is the effective MU. TRIO1 describes only the static behavior of the triode and neglects secondary emission (which would occur at high VG and low VA).

The Heater Parameters Are:

INOM	The nominal heater current at nominal voltage.
VNOM	The nominal heater voltage (causing nominal temperature).
LAMBDA	Temperature coefficient of the heater resistance. (normalized to the nominal temperature)
RCOOL	Resistance of the cold heater.
TCTE	The time constant for the heater temperature.
TNOM	The nominal heater temperature in K.
INIT	Initial heater temperature in % of TNOM
W	Work function of the heater, in eV.
ISAT	The saturation current at nominal heater voltage.

Model Notes: B1 delivers the power received by the heater. Only conductive dissipation is considered (no radiative dissipation and back scattered electrons at RF don't heat the cathode), therefore V(7) is a normalized temperature. B4 contains the Richardson-Duschman law, with an exponential containing B=W/k, the Bolzmann's constant being 0.8617e-4 eV/K for Tungsten (see [4]) W=4.5 eV. It may be 2.2 times lower for an oxide-coated cathode (see [3] p 173). B3 delivers the saturation current.

variations of the perveance and amplification factor. The values of B1 and B2 are then used in B4 and B6 which describe the law [3]. B7 takes into account the saturation variations which are seen when the cathode current is very high. B8, B9, and B10 describe the behavior of the grid current when the grid is positive with respect to the cathode. Reasonable grid current behavior is very important for high power applications. B15 and B16 use the values of the aforementioned B elements to establish the currents in the tube terminals.

Figure 7 shows the curve family obtained for the 12AU7 triode. Note, the proper behavior of the current for negative and positive grid voltages. The saturation current value (about 100mA) for nominal voltages and heating currents was fixed

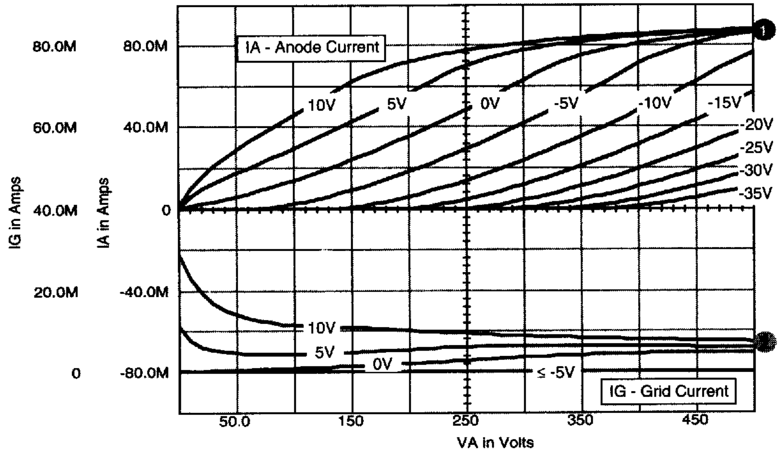

Figure 7, DC characteristics for the 12AU7A triode. The graph clearly shows the nonlinear effects of anode and a grid current versus anode voltage.

arbitrarily; this value is actually dependent on the manufacturing process and tube ageing. The saturation current, Isat, depends on the voltage and heating current. The corresponding heater model is based on thermal considerations and on the Richardson-Duschman law. It is, however, possible (and easy) to suppress this effect, which consumes a large amount of simulation time for little return; in this case the filament (HEAT1) is replaced by a resistor and a voltage source giving Isat, in the subcircuit T12AU7A.

We can see in Figure 8 that the IsSpice4 cross-probed waveforms match pretty well with the real behavior of the triode. An input sinusoid (IK) of (12V) was used resulting in a peak anode current of 52mA.

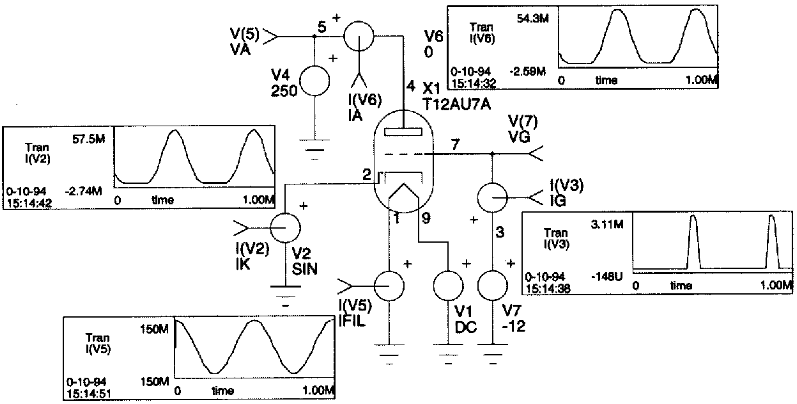

Figure 8, Simple circuit to test the DC and transient characteristics of the new triode tube model. Cross-probed waveforms from IsSpice4 show the performance.

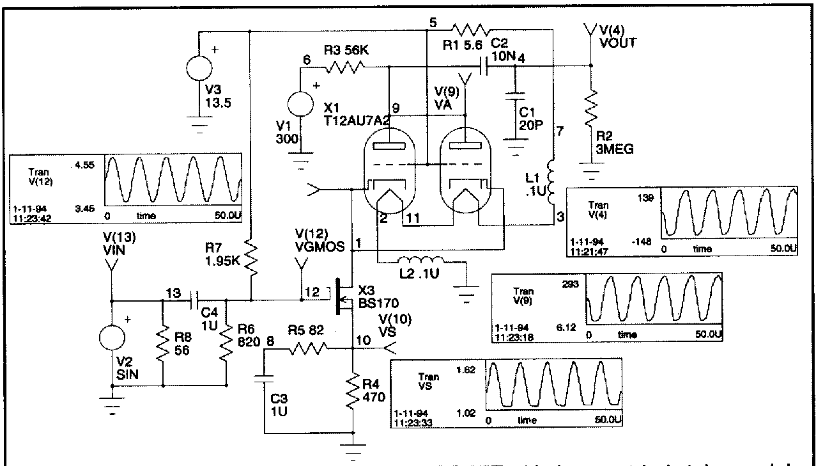

Figure 9, An amplifier combining a power MOSFET with the new triode tube model for a 12AU7A. Waveforms are available either on the schematic or in IntuScope.

A Triode Amplifier

Figure 9 shows an amplifier schematic using a MOS transistor and a double triode (used in a cascode stage), in order to obtain, a high impedance, a very high voltage gain, a high level of feedback, and a good frequency characteristic. The cross probed waveforms show the output voltage, for an input voltage at V(13). In order to speed up the simulation the heater model was replaced with a resistor and voltage source as noted on the previous page. The MOS model is itself a sophisticated subcircuit found it in the Intusoft library. At the 100kHz frequency of the 1V input signal, the output is about 278 V. The curve of the Figure 10 gives the frequency response of the amplifier for small signals.

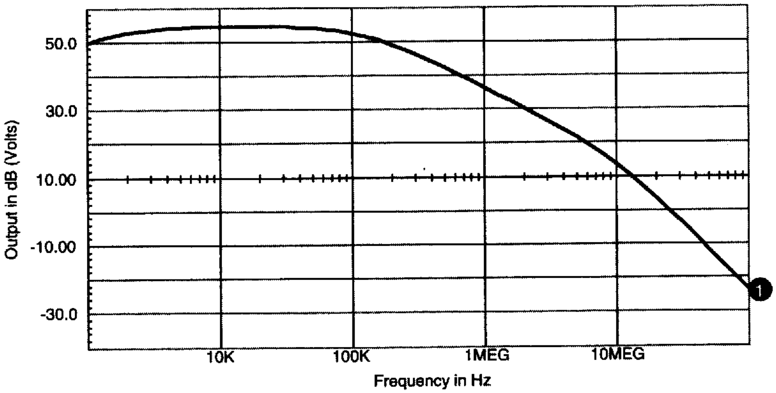

Figure 10, An IntuScope graph of V(4), the small signal response of the tube amplifier shown in Figure 7.

Part II, Conclusions, and References

In the next issue of the *Intusoft Newsletter* we will continue the work started here. A generic and specific model for a pentode will be given along with its characteristic curves. A high voltage amplifier using the pentode will also be simulated. This work vividly shows the extent to which the behavioral capabilities of IsSpice3 and IsSpice4 can reach. Clearly, complex mathematical models of other electronic devices are possible.

References

[1] L.G. Meares, C.E. Hymowitz, "Spice Applications Handbook", Intusoft, 1990, NL-12 February 1989

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[3] Frederick E. Terman, "Electronic and Radio Engineering", McGraw-Hill, 1955

[4] N. Ashcroft, N. Mermin, "Solid State Physics", Cornell University, 1976

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EXCEM provides worldwide services in the fields of electronics R&D, with a focus on RF, theoretical and practical EMC, electronic simulations and DSP. They are also the Intusoft representative in France. Among other things Excem manufactures high-voltage wide-band tube amplifiers for driving high impedance loads (e.g. short E-field antennas).