Analysis of Heathkit TT-1 Transconductance Measurement

The left side of Figure 1 shows a measurement configuration for determining an amplifier tube's transconductance, **Gm**. Transconductance is defined by how much plate current **Ip** changes when grid bias **Vg** is changed a little while plate voltage **Vp** is held constant. This is shown in Figure 1 with characteristic curves for a hypothetical triode. Also shown is the plate resistance, **Rp**. Since the curves are not parallel and straight, the value of Gm and Rp will depend on the "operating point" where the tube biased, and so is measured with small, local variations in Vg. Gm is therefore what is called in the industry as an AC parameter. AC parameters are conventionally written in lower case (as shown in the "AC model") but upper case will be used in this document to minimize typesetting.

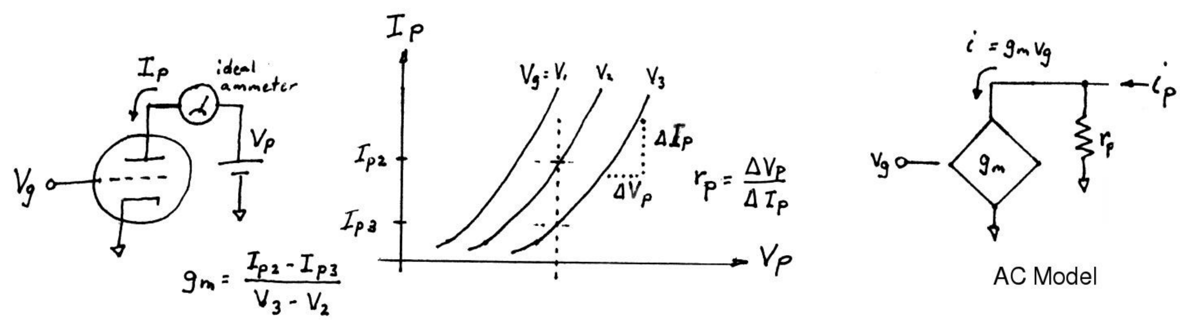

Figure 1. Transconductance Definition and AC Tube Model

For small AC signals, then, the tube's response can be AC modeled as an ideal transconductance amplifier (sink current **I** = Gm*Vg, where **I** and Vg are small AC signals) paralleled with the plate resistance **Rp**, also defined at the operating point (the graph shows Gm and Rp calculated in different regions only for clarity).

The Heathkit TT-1 estimates Gm by applying an AC signal **Vg** (at about 5 kHz) to grid and exciting an AC ammeter response to measure variation in plate current. The left side of Figure 2 is a modified figure from the Operational Manual which shows the components involved.

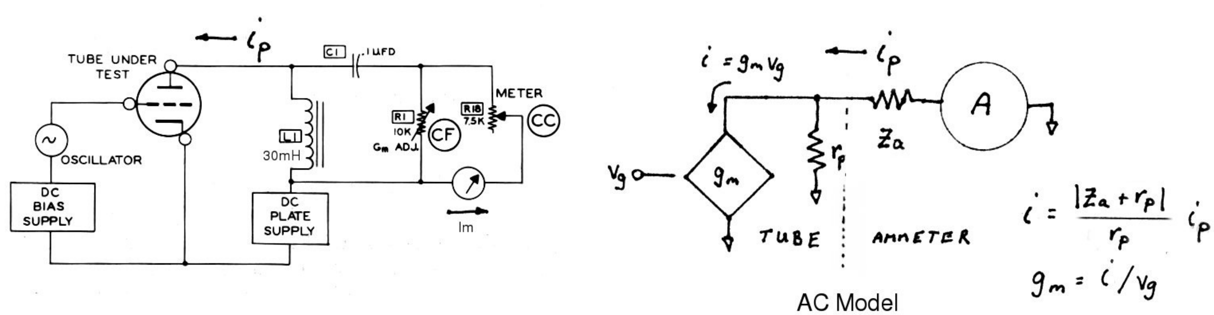

Figure 2. TT-1 Measurement Configuration and AC Model

It should be noted here that the TT-1 measures Gm only around the operating point defined in the tube list entry, and even then relies on expectations of the tube's plate resistance. This is why the TT-1, or any transconductance meter, is not a substitute for characteristic curve tracers (a few of which are commercially available).

The "plate supply" which provides Vp is well bypassed and stays constant during test, so that it doesn't appear in an AC analysis. The screen supply is also bypassed so pentodes show expected Rp when tested. The ammeter network including components L1, C1, CF and CC can be broken down into equivalent resistance **Za**, and an ideal ammeter. This leaves the system AC model as shown on the right of Figure 2.

Rheostat CF, of resistance **Rcf**, is an internal scaling shunt to calibrate the ammeter. “CC” is the front panel “METER” control, with resistance **Rcc**, to scale the ammeter response for particular tubes. The ammeter resistance will be called **Rm**, through which AC current **Im** flows. Coil L1 has an imaginary impedance of magnitude **Xl**, which will make complex analysis necessary. Calculating Za is a lot easier without C1, and it turns out that ignoring C1 incurs only a minor error if METER is kept below a value of 40. This will be looked at later.

Ignoring C1, and seeing that the equivalent ammeter has zero resistance, Za and Rp are in parallel. This makes the circuit, including Rp, simply four parallel branches. The admittances of the branches simply add to yield a total complex admittance Y, the real and imaginary parts Yr and Yi being:

Yr = 1/Rp + 1/Rcf + 1/(Rcc + Rm)
Yi = 1/Xl

and the magnitude of the total being:

Y = sqrt (Yr^2 + Yi^2),

where “sqrt” is the square root operator.

The fraction of current which goes through the ammeter is the ratio of the admittance of the meter branch, which is 1/(Rcc + Rm), to the magnitude of total admittance, so that

I = Gm * Vg = Im * Y * (Rcc + Rm),

Gm = Im * Y * (Rcc + Rm) / Vg (1)

Therefore, the TT-1 has to assume a value for Rp to estimate Gm. It turns out that Rp doesn't have much of an effect when larger than a few Kohms (as is usually the case), and hopefully anything that greatly affects Rp will already cause abnormal Gm measurements.

Let's look closer at the terms that figure in equation (1):

Rp has to be manually measured or taken from tube data at the same operating point and configuration as it is tested in the TT-1. Many tubes are not tested in amplifier configuration on the TT-1 (such as “Whole Tube” tests) and it's possible that some pentodes may be tested in triode mode (Vp to both plate and screen grid).

Rcf: Control CF has a maximum value of 10K and measured 6.15K in the instrument studied after calibration.

Rcc: Control CC has a 7.5K linear taper and is marked from numbers 0 to 50 on the METER knob, where 50 yields Rcc = 0. Values close to 50 (e.g. more than 45) should be avoided as the pot taper becomes inaccurate due to end-of-turn dead zone (**Note**: the METER knob should be set to read 50 at the point where the meter needle stops rising when increased, as in the calibration instructions), touchy meter response and the effect of C1 becoming significant (see note on ignoring C1 below). In terms of the METER knob value, then, Rcc = 0.15 * (50 – METER) Kohms.

Rm: For the ammeter, AC tests show that it looks resistive and is not sensitive to test frequency (up to 15 kHz, anyway). It’s a bit nonlinear, however (given its internal diode rectification), so that for meter readings around 500, it looks like a 2 Kohms, and for a reading of 3,000, it’s 750 ohms. For the range of 1,000 to 2,000 however, it looks pretty close to 1000 ohms (within 15%). Probably because of this, the tube tables are set up so that most reject points (R.P.) are between readings of 1,000 and 2,000. For analysis, then, the meter resistance **Rm** is considered 1,000 ohms. The ammeter has an AC full scale of about 1 milliamp where it reads 3 millimhos, so Im = Reading/3.

Yi: If Vg is sinusoidal, coil impedance Xl = 2*pi*frequency*inductance. The coil on the TT-1 tested measured about 30mH at audio frequencies, and this should be the case for other TT-1s as well. The source frequency on the TT-1 studied was about 7 kHz, making Xl about 2j*pi*7K*0.03 = 1320j ohms. This makes Yi = 0.76 millimhos for this TT-1. In general, Yi = 5.3/F millimhos, where F is the frequency of signal Vg in kHz.

Vg: An actual oscilloscope trace of grid signal Vg shown in Figure 3 looks anything but sinusoidal and it appears that this is the intended signal shape! Not only is its rms value difficult to measure but its strong harmonics will also contribute significantly to the meter response in a tough to calculate way. Since the circuit is linear, however, this will translate into a calibration factor **K** (to be determined experimentally) which won't change with instrument settings. SIG settings of 1, 2, 4 and 8 correspond to Vg of 2, 1, 0.5 and 0.25V rms nominal, so that after including K, Vg = 2*K/SIG.

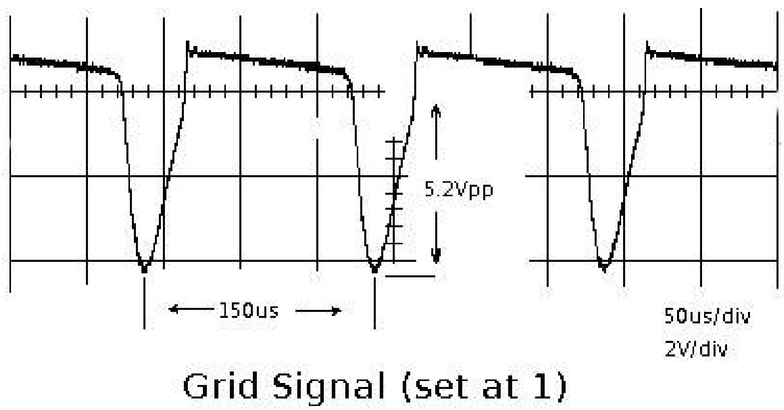

Figure 3. TT-1 Transconductance Test Grid Signal

Applying the equivalences for the meter and Vg to equation (1):

Gm = Reading * K * SIG * Y * (Rcc + Rm) / 6
= Reading * Me, so that

Me = K * SIG * Y * (Rcc + Rm) / 6

is the estimated multiplier that, when applied to the meter reading, you'd expect to give an accurate reading of the transconductance. This should correspond to the multipliers, **M**, given in the TT-1 tube lists.

An aside on why C1 can be ignored: A full network calculation shows that the presence of C1=0.1uF (compared to a short) increases the meter current about 14%, 5% and 3% for METER=50, 40 and 30 respectively, and that this is not too sensitive to test frequency. In fact, percent error fits pretty close to 80/(57 – METER). This is splitting hairs, though, and including this has little effect on final results. Given uncertainty in Rm and Vg, and given that METER values above 45 are avoided, this constitutes an error of around 5%, which can be considered part of K. Another reason to avoid METER settings above 45 is that the exact pot value becomes inaccurate and touchy near it's high extreme.

To recap, then, for the TT-1 studied:

Gm = Reading * Me (micromhos)
Me = K * SIG * Y * (Rcc + Rm) / 6, where

K = a constant to be determined from comparison of Me with chart values M.
Rcc = 0.15 * (50 – METER) Kohms
Rcf = Value of rheostat CF, measured after calibration (6.15K on studied TT-1)

Rm = 1K for readings from 1,000 to 2,000

Yi = 5.3/(frequency of Vg in kHz) millimhos (0.76mmhos on studied TT-1)
Yr = 1/Rp + 1/Rcf + 1/(Rcc + Rm)
Y = sqrt (Yr^2 + Yi^2),

Between different TT-1s, it is expected that Rcf, Yi (dependent on frequency of Vg) and K will be different. DETERMINING THESE IS DONE AT THE READER'S OWN RISK. Rcf would be measured directly after calibration (measurement requires desoldering one side of the pot). The frequency of Vg might be measured simply by probing a test socket pin assigned to grid (selector position 5), referenced to a cathode pin (selector position 1). To estimate Yi, it's probably safe to assume that L1 will look about 30mH on all TT-1. K is determined by measuring a well characterized amplifier tube, such as a triode, with well known Gm and Rp, and setting K to make Me = M.

Results

Calibration of the TT-1 studied was verified by ensuring that transconductances measured by the TT-1 and those derived from a "curve-traced" 12AT7 tube showed good agreement (within 5%). This yielded K= 1.6.

The spreadsheet which companions this article, "GmAnalysis.xls", contains TT-1 tube list entries where multiplier M is off by expected multiplier Me by more than a factor of 2 (Me/M > 2 or Me/M < 0.5). At the top of both pages of the worksheet, a heavy bordered box encloses system parameters, such as Rcf, Rm, K, etc. to fiddle with. The first 5 rows are examples of "good" entries (with 6AS7 as an example of very low Rp). Grid and Plate values have been derived to make it easy to find "book" Gm from curves or a catalog. When available, "Book Gm" is listed beside Gm estimated from the tube list (Est. Gm = 1.5 * R.P. * M) to see if they match. Several columns have intermediate calculations. The list is sorted in order of the ratio Me/M. Note that Y doesn't change much for normal Rp and METER < 45, which will be convenient for calculations below. Rp = 9K is assumed for triodes and Rp=100K for pentodes when actual values haven't been entered.

Spreadsheet "GmAnalysis" shows that about 8% of the 3000 TT1 tube list entries are suspect because Me and M disagree by a factor of 2 or more. A number of these were resolved when proper Rp values, which turned out to be quite low (below 2K, such as with 6AS7), were entered. Remaining cases might be due to one of the following:

i) Typos in transcribing from the tube list to the spreadsheet.
ii) Some tests operate the tube in non-standard modes, such as with heptodes and "whole tube" entries, and probably try to infer Gm in normal operation from this with an implicit factor.
iii) Similar to ii), test conditions may not reflect some accepted nominal condition, and an implicit factor is applied to derive nominal Gm. For example, large tubes may be measured at below normal plate current (and transconductance), and the multiplier may attempt to estimate nominal Gm from this nonstandard setup.
iv) R.P. under 1000 corresponds to Rm > 1K (Rm~2K for meter=500) and slightly high Me/M values.
v) As mentioned in the beginning, AC applied to grid during Gm measurement should be small compared to the DC grid bias. If it is not, the tube grid could be swung positive and/or to cutoff, which will tend to reduce the Gm measurement and require a larger than expected METER value. This probably happens with low Gm tubes tested with DC low bias and SIG=1 setting, yielding low Me/M, and represents the TT1's least capable mode.

Examining several odd Me/M values exposed many errors in Heathkit's tube list. It appears that operating conditions from the tube list mostly match those reported in compilations such as General Electric's "Essential Characteristics". Since this book also lists operational Rp and transconductance values, errors in multipliers are quickly revealed. Since R.P. is set to correspond to 2/3 nominal reading, then the proper multiplier is (2/3)*Gm/RP. If, for example, R.P. is 1000 and nominal Gm is reported to be 3000, this suggests a multiplier of (2/3)*Gm/R.P. = x2. If Me/M is also close to 2, this is a very strong indicator of what the multiplier should be.

If the multiplier appears correct, an Me/M which is off by a power of 2 (0.12, 0.25, 0.5, 2, 4, or 8) is a sign of SIG value typo (apart from Case v) above).
Errors in METER are harder to find. “23” might be appear on the list when “32” was intended. If a tube appears on more than one Heathkit list with different METER entries, analysis might show which one is right.

If an entry is suspect, try to find an entry for an equivalent tube. For example, an entry for 8BH8 was very suspect but that for the 6BH8 equivalent looks fine, so the entry for 6BH8 was adopted for 8BH8 (except for filament, of course). Routinely comparing entries for equivalents exposed errors such as PLATE=”O” when it should have been “D”.

Typos in SELECTOR can be laborious to find but some automated checking ferreted out several errors. For example, selector values for any numeric SIG value (1, 2, 4 or 8) should usually have a “1”, must have a “3” and a “5”, rarely more than one occurrence of “3” or “5” and always a “6” and “7”.

Even when typos have been eliminated, spreadsheet page “Suspect” examines some remaining cases of abnormal Me/M. The rightmost column proposes what the problem might be.

Generating List Values for New Tubes

The formula for Me can be used with known tube characteristics and measurements made on a particular TT-1 (frequency of Vg and Rcf) to make TT-1 amplifier tube list entries for new tubes or new test conditions. Once the appropriate TT-1 test conditions and biases for the tube are decided on, the nominal Gm and Rp for the tube are derived from characteristic curves (as in Figure 1) at the operating point or from a data book which specifies the operating point. Gm and Rp will change with test conditions so the operating point should be close.

The reject point (R.P.) is 2/3 of nominal Gm. A multiplier M should be chosen so that Gm falls in the meter mid-range (1000 to 2000). SIG should be chosen so that the excursion of Vg doesn't cause the grid bias to become positive. Figure 3 shows a positive excursion relative to average of about 2 volts for SIG=1, so the grid bias should be more negative than -2 in this case (or -1, -.5 or -.25 for SIG=2, 4, or 8 respectively). METER values greater than 45 should be avoided.

Example:

A 12AU7 is to be tested at Vp = 90V (PLATE knob position 'C') at a bias of -1.2V (BIAS = 12L). Gm and Rp measured from characteristic curves show Gm = 2700 and Rp = 8K. M = 2 yields a R.P. of about (2/3)*Gm/M = 900, which is a bit low on the meter but this accommodates nominal readings of Gm/M=1350 well. SIG should not be 1 due to the shallow bias, so lets try SIG=2.

$$M = K * SIG * Y * (Rcc + Rm) / 6$$

It's hard to invert this equation to solve for Rcc since it appears in Y, but Y does not change very much for METER settings less than 45 and normal Rp values of a few Kohms or more. If one starts with a reasonable initial guess of Rcc to calculate Y (say, a few Kohms), Rcc converges very quickly after an iteration or two.

In this example, starting with Rcc=1.5K (METER=40) as a first guess, Y=0.96 mmho. Using Rm = 1K near midrange, K=1.6 and SIG=2:

2 = 0.51 * (Rcc + 1), Rcc in Kohms
Rcc = 2.9K = 0.15K * (50 - METER), so that
METER = 31

Y for Rcc=2.9K is 0.88 mmho, and calculating again yields METER=28, which won't change much in subsequent iterations. The tube entry would then be:

12AU7	C	12L	6.3	28	2	PGK77-3516	900	x2.