

## Getting More from Tube Data Sheets...by Earles L. McCaul

### • 6L6GC Class AB<sub>1</sub>

There is a lot more information packed away in a vacuum tube data sheet than what you see in print. Consider, for example, a push-pull power amp that uses a pair of 6L6 tubes. If we set the plate supply voltage to 450 volts, drop 50 volts to supply the screens, give it -37 volts of DC bias, and use an output transformer with an impedance of 5.6k plate-to-plate, then we get a power amp with the following characteristics:

zero-plate voltage	450 volts
screen voltage	400 volts
DC grid bias	-37 volts
signal AC grid voltage at full power	35 volts peak
zero-signal plate current per tube	58mA
maximum-signal plate current per tube	105mA
zero-signal screen current per tube	2.8mA
maximum-signal screen current per tube	11 mA
output transformer plate-to-plate impedance	5.6k $\Omega$
total harmonic distortion	1.8 percent
maximum-signal power output	55 watts
maximum-signal plate voltage	262 volts RMS
effective load for each tube	1.25k $\Omega$
average transconductance per tube	6mA/volt
voltage amplification factor	7.5
effective tube resistance	1.25k $\Omega$
dynamic plate resistance	23.5k $\Omega$
effective amplification factor	141
effective peak AC plate voltage	370 volts
minimum plate voltage at the knee of the zero-grid-voltage curve	80 volts
percent of max plate dissipation under zero-signal conditions	87 percent
zero-signal plate-to-screen current ratio	21 to 1
full-power plate-to-screen current ratio	10 to 1
tube perveance	10mA/volt <sup>3/2</sup>
percent of maximum screen dissipation at full power	66 percent
percent of maximum plate dissipation at full power	69 percent
plate efficiency	65 percent
plate conduction angle	202.5 degrees, 13 percent above Class B

This is a lot more information than GE gives us in its 6L6GC data sheet<sup>[1]</sup>, but we didn't need to build the amp to get it. In the next section we will demonstrate how to dig deeper into a data sheet to extract these useful numbers.

<sup>1</sup> GE 6L6GC Beam Pentode, data sheet ET-T1515A (3-59).

## • Crunching the Numbers

Here is what is contained in the GE's 6L6GC data sheet:

plate voltage	450 volts
screen voltage	400 volts
grid number 1	-37 volts
peak AF grid-to-grid voltage	70 volts
zero-signal plate current	116mA
maximum-signal plate current	210mA
zero-signal screen current	5.6mA
maximum-signal screen current	22mA
effective plate-to-plate resistance	5.6k $\Omega$
total harmonic distortion	1.8 percent
maximum-signal power output	55 watts

Some clarification is in order:

a) Peak AF grid-to-grid voltage is a voltage for two tubes ( $V_{gg}$ ); the grid-voltage seen by each single tube is one-half of this value ( $V_g$ ). The product of  $V_g$  and  $g_m$  is RMS plate current<sup>[2]</sup>.

b) Zero-signal numbers are for two tubes; the value for a single tube is one-half of those values.

c) Maximum-signal numbers are RMS values for both tubes (one conducting, one in cutoff), the average value for a single tube is one-fourth of those values.

d) Average value of combined zero- and maximum-signals is approximated as:

$$X(\text{avg}) = (X_q/2 + \Delta X/4).$$

**NOTE:**  $\Delta$  represents AC-change in voltage ( $V_{AC}$ ) or current ( $I_{AC}$ ) and q denotes quiescent or idle values ( $V_{DC}$  or  $I_{DC}$ ).

From the maximum-signal power output ( $P_o$ ) 55 watts and maximum-signal plate current ( $\Delta I_p$ ) we can determine the maximum-signal plate voltage ( $\Delta V_p$ ):

$$\Delta V_p = P_o / \Delta I_p = (55W / 0.210A_{RMS}) = 261.9 V_{RMS}$$

The effective plate-to-plate load resistance ( $R_{pp}$ ) is 5.6k ohms, so the single-tube plate load resistance ( $R_p$ ) is one-fourth of that value, 1.4k ohms; however, the actual effective value ( $R_p'$ ) seen by each tube is a somewhat lower value:

$$R_p' = \Delta V_p / \Delta I_p = (261.9V_{RMS} / 0.210A_{RMS}) = 1247\Omega \approx 1.25k \Omega$$

<sup>2</sup> AF signal voltage  $V_g$  is PEAK-value and transconductance  $g_m$  is RMS-value; their product is RMS plate current:  $V_{g(pk)} \times g_{m(RMS)} = I_{p(RMS)}$ .

So, the load factor (%) is 89 percent:

$$(\%) = R_p' / R_p = (1247\Omega / 1400\Omega) = 0.89$$

From the maximum-signal plate current ( $\Delta I_p$ ) and the peak AF grid voltage seen by each single tube ( $\Delta V_g = V_{gg}/2$ ) we can determine the average transconductance ( $g_m$ ) value for each tube:

$$g_m = \Delta I_p / \Delta V_g = (0.210A_{RMS} / 35V_{pk}) = 0.0060A/V = 6mA/V$$

From the maximum-signal plate voltage ( $\Delta V_p$ ) and single tube peak AF voltage ( $\Delta V_g$ ) we can determine the voltage amplification (AV) factor, or circuit gain:

$$AV = \Delta V_p / \Delta V_g = (261.9V_{RMS} / 35V_{pk}) = 7.4829 \approx 7.5$$

or, AV may also be found from the in-circuit effective tube  $r_p'^{[3]}$  and  $g_m$  values:

$$AV = r_p' \times g_m = (1247 V/A \times 0.0060 A/V) = 7.4820 \approx 7.5$$

Since circuit gain (AV) is synonymous with effective tube gain ( $\mu_2$ ), we can determine the loaded or effective tube resistance ( $r_p'$ ) in multiple ways:

$$\mu_2 / AV = 141 / 7.5 = 18.8 \dots \text{and} \dots r_p / r_p' = 23.5k / 1.25k = 18.8$$

$$\mu_2 / AV = r_p / r_p'$$

$$r_p' = r_p \times AV / \mu_2 = (23.5k \times 7.5 / 141) = 1.25k \Omega$$

$$r_p' = AV / g_m$$

$$r_p' = (7.483 / 0.0060 A/V) = 1247\Omega \approx 1.25k \Omega$$

Back solving from the load factor equation, we can determine the dynamic plate resistance ( $r_p$ ) of the tubes:

$$(\%) = ((r_p / (R_p + r_p))^2$$

$$r_p = R_p \times \text{SQR}[(\%)] / (1 - \text{SQR}[(\%)])$$

$$r_p = 1.4k \times \text{SQR}[0.8907] / (1 - \text{SQR}[0.8907]) = 23,497\Omega \approx 23.5k \Omega$$

Because of the higher  $r_p$  value (than 22.5k $\Omega$ ), the open-circuit amplification factor ( $\mu_2$ ) of these tubes is slightly greater (+4.4%) than the published bogie value of 135:

$$\mu_2 = g_m \times r_p = (0.0060 A/V \times 23,497 V/A) = 140.98 \approx 141$$

The effective plate voltage change is 261.9V<sub>RMS</sub>, so the peak plate voltage change is 370.4V<sub>(pk)</sub>:

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<sup>3</sup> NOTE:  $r_p'$  is the in-circuit *loaded* condition when  $r_p' = R_p'$  and is not the same as  $r_p$  which is the tube-only *unloaded* condition where  $r_p = \mu_2/g_m$ .

$$\Delta V_{p(pk)} = \Delta V_{p(RMS)} \times \text{SQR}[2] = 261.9 V_{RMS} \times \text{SQR}[2] = 370.4 V_{(pk)}$$

Assuming the load line is centered through the plate knee voltage (condition of maximum power and minimum distortion), the knee voltage can be determined by subtracting the peak plate voltage change from the plate voltage:

$$V_{p(knee)} \approx V_p - \Delta V_{p(pk)} = (450V - 370.4V_{(pk)}) = 79.6V \approx 80 V_{DC}$$

This agrees well with the rule-of-thumb value derived by dividing the screen-grid voltage ( $V_s$ ) by five:

$$V_{p(knee)} \approx V_s / 5 = (400V / 5) = 80V_{DC}$$

The quiescent or idle plate current ( $I_{pq}$ ) for a single tube is one-half of the two-tube zero-signal plate current, or 0.058 amps, and the idle plate voltage ( $V_{pq}$ ) is 450 volts. This means the tubes are idling at a rather hot value of 87 percent of their maximum plate dissipation ( $P_{pd}$ ) value:

$$\% (P_d) = (I_{pq} \times V_{pq}) / P_{pd} = (0.058A \times 450V) / 30W = 0.87 \text{ or } 87\%$$

The respective zero- (idle) and maximum-signal plate-to-screen current division ratios are approximately 21:1 and 10:1:

$$D_q = I_{pq} / I_{sq} = (0.058A / 0.0028A) = 20.71 \approx 21:1$$

$$D_m = \Delta I_p / \Delta I_s = (0.210A_{RMS} / 0.022A_{RMS}) = 9.55 \approx 10:1$$

The Perveance (K) value<sup>[4]</sup> for these tubes is found by using the triode values and the Child-Langmuir 3/2-Law equation:

$$I_{pq} = K \times (V_{gq} + V_{pq}/\mu)^{3/2}$$

$$K = (0.072A) / (-14V + 250V/7.99)^{3/2} = 0.0010 A/V^{3/2}$$

Assuming no screen grid resistors are used (worse-case situation), the screen-grid dissipation at maximum-signal operation is approximately two-thirds of its maximum rated dissipation rating of 5W:

$$I_{s(avg)} \approx (I_{sq}/2 + \Delta I_s/4) = (5.6mA/2 + 22mA_{RMS}/4) = 8.3mA$$

$$P_{sd} = I_{s(avg)} \times V_s = (8.3mA \times 400V) = 3.32W$$

$$\% (P_s) = (3.32W / 5W) = 0.664 \text{ or } 66\%$$

The plate efficiency (%P) is quite high, at approximately 65 percent:

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<sup>4</sup> Perveance of a vacuum tube is the ratio of its cathode area to its anode distance-squared:  $K = (2.33 \times 10^{-6})A/d^2$  and is measured in units of amps-per-volt<sup>3/2</sup> ( $A/V^{3/2}$ ).

$$\%P = (\pi/4) \times (\Delta V_{p(pk.)} / V_p)$$

$$\%P = (\pi/4) \times (370.4V / 450V) = 0.647 \text{ or } 65\%$$

At maximum-signal output, the average plate dissipation ( $P_{p(avg)}$ ) for each tube is 20.8 watts, or 69 percent of its maximum rating:

$$P_{p(avg)} = \Delta I_{p(avg)} \times (V_p - \Delta V_{pRMS})$$

$$P_{p(avg)} = (116mA/2 + 210mA/4) \times (450V - 261.9V) = 20.79 \approx 21W$$

$$\%P_p = (20.8W / 30W) = 0.693 \text{ or } 69\%$$

At maximum-signal, the average plate and screen currents are:

$$\Delta I_{p(avg)} = (116mA/2 + 210mA/4) = 110.5 \text{ mA}$$

$$\Delta I_{s(avg)} = (5.6mA/2 + 22mA/4) = 8.3 \text{ mA}$$

and the average plate and screen voltages are:

$$\Delta V_{p(avg)} = V_p - \Delta V_{pRMS} = (450V - 261.9V) = 188.1V$$

$$\Delta V_{s(avg)} = V_s = 400V \text{ (assuming no screen-grid resistors used)}$$

thus, the average plate- and screen-dissipation values for each tube are:

$$P_p = 20.8W \text{ or } 69\% \text{ of maximum rating}$$

$$P_s = 3.32W \text{ or } 66\% \text{ of maximum rating}$$

At the optimum conditions of maximum power and minimum distortion, the circuit AV value may be approximated as the triode mu value times the plate load division ratio:

$$AV = \mu_1 \times (r_p / (R_p + r_p)) = 7.99 \times (23.5k / (1.4k + 23.5k)) = 7.541 \approx 7.5$$

The plate load division ratio very closely approximates the ratio of plate  $\mu_2$  and screen grid  $\mu_1$  ratios and is the square root of the load factor (%) value:

$$\mu_2 \approx \mu_1 \times r_p / (R_p + r_p)$$

$$\mu_2 / \mu_1 \approx r_p / (R_p + r_p)$$

$$\mu_2 / \mu_1 \approx (7.482 / 7.99) = 0.9464$$

$$\mu_2 / \mu_1 \approx \sqrt{(\%)} = \sqrt{(0.89)} = 0.9434$$

So, the plate load division ratio, the plate  $\mu_2$  and screen  $\mu_1$  ratio, and the square root of the load factor are identical values.

Actual zero-signal (idle) plate and screen current division ratio verifies the approximation:

$$D = 1 - (I_{sq} / I_{pq}) = 1 - (5.6mA / 116mA) = 0.9517$$

The plate Conduction Angle (CA) identifies where, within the Class-AB limits between Class-A and Class-B operation<sup>[5]</sup>, the tubes are being operated:

$$CA = 2 \times \text{ACOS}[ -I_{pq(\text{DC})} / \Delta I_{p(\text{pk})} ]$$

$$CA = 2 \times \text{ACOS}[ -58\text{mA} / 297\text{mA} ] = 202.5 \text{ deg.}$$

Plate efficiency increases toward a maximum value of 78.5 percent<sup>[6]</sup> as the conduction angle approaches Class-B operation. Here, the plate efficiency is 65 percent at a plate conduction angle of 202.5 degrees, or 13 percent of the way between Class-B and Class-A operation.

$$\%(\text{AB}) = (CA - 180^\circ) / 180^\circ = (202.5^\circ - 180^\circ) / 180^\circ = 0.125 \text{ or } 13\% \text{ above Class-B}$$

The peak maximum-signal plate and screen currents and voltages are:

$$\Delta V_{p(\text{pk})} = \Delta V_{p\text{RMS}} \times \text{SQR}[ 2 ] = 261.9\text{V} \times \text{SQR}[ 2 ] = 370.4\text{V}_{(\text{pk})}$$

$$\Delta V_{s(\text{pk})} = I_{sq} = 400\text{V}_{\text{DC}} \text{ (assuming no screen grid resistors)}$$

$$\Delta I_{p(\text{pk})} = \Delta I_{p(\text{RMS})} \times \text{SQR}[ 2 ] = 0.210\text{A} \times \text{SQR}[ 2 ] = 0.297\text{A}_{(\text{pk})}$$

$$\Delta I_{s(\text{pk})} = \Delta I_{s(\text{RMS})} \times \text{SQR}[ 2 ] = 0.022\text{A} \times \text{SQR}[ 2 ] = 0.031\text{A}_{(\text{pk})}$$

To estimate a new control-grid bias voltage necessary to produce a different idle current:

$$Vg = (0.9) \times (3/2) \times (I_{pq} / g_m) - (V_s / \mu_{11})$$

$$Vg = (0.9) \times (3/2) \times (0.058\text{A} / 0.0060 \text{ A/V}) - (400\text{V} / 7.99)$$

$$Vg = (1.35 \times 9.667\text{V} - 50.06\text{V}) = -37.01\text{V} \approx -37\text{V}_{\text{DC}}$$

Quite a few things the data sheets don't tell us, aren't there?

<sup>5</sup> Class-A operation is 360 degrees, Class-B operation is 180 degrees, and Class-AB operation is *between* 180 and 360 degrees. Typical Class-AB1 operation is between 190-205 degrees.

<sup>6</sup> Maximum theoretical efficiency is  $\pi/4 = 0.7854$  or 78.5 percent.