

All around the world, tube audio gear is gaining popularity with audiophiles. With the irresistible glamour of tubes in mind, we decided to reconsider the accomplishments of audio design of the last seven decades, and to apply current technologies to it.

We believe that the surprising results obtained in the past are, in part, due to the lack of technology of the times, when practical subjective outcomes were the norm. By maintaining the same approach, using a PC, we can learn from the past and have a good time. As you can see from the references, the theory that follows was already in place; all we did was to add the computer.

Curve Calculation

You can simulate and calculate the harmonic distortion of a single tube amplifier by experimentally measuring the plate characteristic curves and load (Fig. 1). You can then construct the dynamic transfer characteristic curve ("dynamic curve"), which describes the variation of the plate current versus that of the grid voltage, and evaluate the harmonic distortion (related to both certain quiescent conditions and the load).

Let's start with the procedure to obtain the dynamic curve. You should note that a different dynamic curve is traced for each operating point Q and dynamic load line considered. If we have N output measured curves, we can simply approximate the dynamic curve by plotting the N points that are the intersects of the load line with the output curves in a plane with the Ia-Vg axis

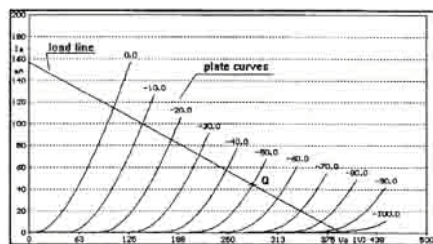


FIGURE 1: Plate curve versus load.

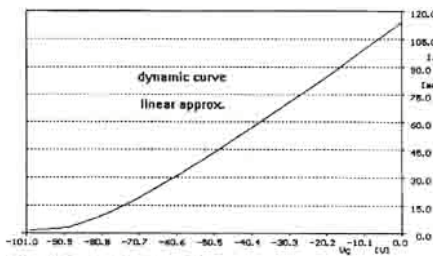


FIGURE 2: Plotting the dynamic curve.

(Fig. 2) and joining them with lines. We will see later how to mathematically approximate this data.

The mathematical relationship of the dynamic transfer curve is:

$$\delta I_a = B_1 \times \delta V_g + B_2 \times \delta V_g^2 + B_3 \times \delta V_g^3 + B_4 \times \delta V_g^4 + \dots \quad (1)$$

$$\delta V_g = V_{g_{MAX}} \times \cos(\omega t) \quad (2)$$

$$\delta I_a = H_1 \times \cos(\omega t) + H_2 \times \cos(2\omega t) + H_3 \times \cos(3\omega t) + H_4 \times \cos(4\omega t) \dots \quad (3)$$

Assuming that grid voltage variations can be expressed [as in (2)] using trigonometric transformations, we can rewrite (1) and obtain the final expression of the dynamic curve (3). These three equations tell us that, with a power series to approximate the curve, and a sinusoidal input, you can derive the distortion H coefficients from the

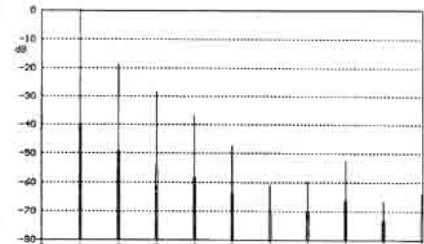


FIGURE 3: H coefficients.

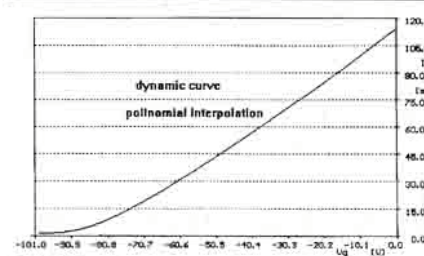


FIGURE 4: Interpolation function.

PLAYING WITH CURVES

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expression of the dynamic curve. In other words, a close relationship exists between harmonic distortion and the shape of this curve.

Simulation

First, we computed the distortion coefficients and the interpolating polynomial. If, from the load line, you have N input points, following a method first described by Espley,¹ you can calculate distortion coefficients till the (N-1) order. You must solve a linear system of N equations (the (3) evaluated in each input point) with N unknowns (the distortion coefficients). The simulation software we use calculates to the tenth harmonic.

Once you determine the H coefficients, you can display them (Fig. 3) and figure the total harmonic distortion factor. A frequent problem is that the number N of measured curves is quite low, and we need to simulate tube behavior at a condition for which measured data is unavailable.

In Fig. 1, with only 11 measured curves and the operating point Q, you can achieve accurate simulation only with maximum output power (i.e., maximum grid voltage swing). While relying on the same measured points, you could simulate for smaller inputs but lose reso-

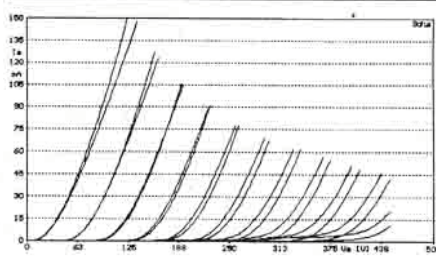


FIGURE 5: The two side limits of ten tubes.

TABLE 1

C80 MEASUREMENTS

Vak dc :	250	Ia dc :	60	Vg dc :	-40.2		
Vak rms	Ia rms	Zp	P	THD M	THD S	E THD %	
83.400	42.000	1985.714	3.503	5.520	5.960	8.0	
60.000	30.170	1988.731	1.810	3.360	3.480	3.6	
89.430	36.150	2473.859	3.233	3.880	4.200	8.2	
63.760	25.860	2465.584	1.649	2.630	2.680	1.9	
94.260	31.200	3021.154	2.941	3.180	3.210	.9	
66.980	22.280	3006.284	1.492	2.260	2.110	6.6	
97.660	27.500	3551.273	2.686	2.610	2.570	1.5	
69.270	19.600	3534.184	1.358	1.910	1.760	7.9	
100.000	24.890	4017.678	2.489	2.320	2.220	4.3	
70.900	17.700	4005.650	1.255	1.730	1.540	11.0	
101.910	22.860	4458.005	2.330	2.030	1.950	3.9	
72.170	16.200	4454.938	1.169	1.510	1.380	8.6	

lution and be limited to particular cases.

An interesting test is to evaluate the distortion at one-half the output power, with a grid voltage of about 0.7 as its maximum value. The most straightforward way to do this without measured points is to use mathematical equation (1). This interpolating polynomial will be evaluated in N points that the simulation software processes as the measured ones. The final result is simulation data uniformity and the ability to manipulate the operating conditions.

As stated before, knowing the distortion H coefficients lets us compute, with direct trigonometric calculations, the B coefficients of the interpolation function (Fig. 4). The approximation, in practical cases, is very good and permits the simulation of the output tube distortion curve versus the input excitation level.

Real Life

Our starting point was the simulation of

a tube amplifier output stage in single-ended format. This is the simplest and most popular output configuration, at least per number of components. Output devices in amplifiers don't operate completely in a predefined state. Therefore, they are better-suited than others for computer simulation.

We chose a direct-heated triode, the 2A3, because it is readily available, inexpensive (at least the Chinese ones), and has a good sound reputation. With ten 2A3s on the workbench and the *RCA Receiving Tube Manual* open to the right page, we measured the plate characteristics of all the tubes as they came out of the box (Fig. 5). All ten tubes had lower gm than the RCA book. Testing with a TV-2B Electron Tube Tester for gm indicated all the tubes should be replaced.

Not to worry. We classified the ten tubes A to L, chose tube C to represent all its colleagues, and continued. Choosing among ten pieces is better than one or two, but whether our collection is representative of the market is debatable.

The Test Bench

Figure 6 shows the test setup. With the variable power supply and R8, we could select virtually any useful operation point.

We verified the SE output trans-

former for distortion at the test frequency (1kHz) under the worst DC current and output level conditions, and used R1 for both DC and AC current sensing. The battery-powered Fluke 99 digital scope verified floating measurement between the variable power supply output and points C and B, which was the AC plate voltage measuring point.

R2 is a series of 1Ω 1% resistors switched with alligator clips to obtain a load reflected on the SE transformer primary from between 2k and 4.5k in 0.5k steps. We used CLIO, an FFT analyzer, to measure output THD, and adjusted the power amplifier output level each time for Vg bias × 2 P/P and 3dB lower (half power).

Tube C was burned in for one night at

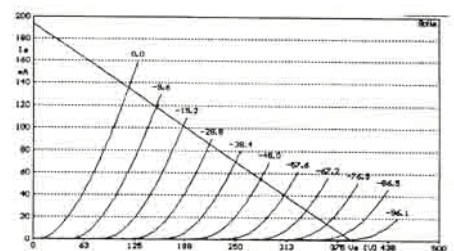


FIGURE 7A: C96 plate curves.

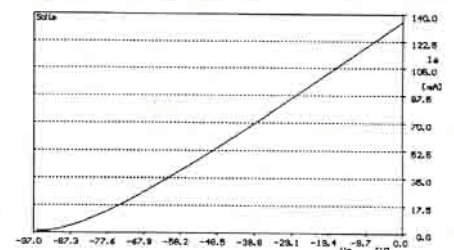


TABLE 2

C86 MEASUREMENTS

Vak dc : Ia dc : Vg dc :

Vak rms	Ia rms	Zp	P	THD M	THD S	E THD %
78.700	39.600	1987.374	3.117	13.430	13.290	1.0
59.680	30.170	1978.124	1.801	6.030	6.400	6.1
87.400	35.760	2444.072	3.125	8.920	9.410	5.5
64.370	26.400	2438.258	1.699	4.440	4.680	5.4
94.570	31.560	2996.515	2.985	5.900	6.280	6.4
68.380	22.850	2992.560	1.562	3.450	3.510	1.7
99.830	27.860	3583.274	2.781	4.330	4.530	4.6
71.050	20.320	3496.555	1.444	2.780	2.760	.7
102.240	25.900	3947.490	2.648	3.690	3.870	4.9
72.930	18.520	3937.905	1.351	2.400	2.460	2.5
104.800	23.550	4450.106	2.468	3.210	3.160	1.6
74.580	16.780	4444.577	1.251	2.180	2.130	2.3

TABLE 3

C96 MEASUREMENTS

Vak dc : Ia dc : Vg dc :

Vak rms	Ia rms	Zp	P	THD M	THD S	E THD %
95.800	47.250	2027.513	4.527	9.840	9.850	.1
70.420	35.510	1983.103	2.501	5.020	5.120	2.0
103.830	42.280	2455.771	4.390	6.880	6.940	.9
75.330	30.740	2450.553	2.316	3.840	3.810	.8
110.400	37.330	2957.407	4.121	4.910	4.950	.8
79.170	26.810	2953.003	2.123	3.060	2.970	2.9
115.270	33.180	3474.081	3.825	3.870	3.630	6.2
82.500	23.300	3540.773	1.922	2.590	2.440	5.8
118.430	30.000	3947.667	3.553	3.260	3.050	6.4
84.200	21.400	3934.579	1.802	2.280	2.090	8.3
121.060	27.330	4429.565	3.309	2.890	2.520	12.8
85.930	19.450	4417.995	1.671	2.110	1.860	11.8

250V @ 50mA. We sampled plate curves and found no change from the first measurement. This was quite surprising, since in other tests these changed slightly. With a stable tube, we measured three plate curve families to fit three different operation points and took THD and other measurements for six load conditions at full and half power.

The first operating point, C80, was suggested from RCA in terms of plate-to-

cathode voltage 250V and plate current 60mA. The second one, C86, 250V @ 43mA, results from plugging the tube into the socket with Va and R8 set according to *RCA Tube Manual* plate curves. The third one, C96, 280V @ 55mA (16W), satisfies our wish of working just a little bit over the limit.

Results

Tables 1–3 show the results of measure-

ments and simulation of the three operation conditions. For an explanation of terms, see the glossary accompanying this article. We measured at half power, reducing the tube input level 3dB (real half-power output is obtained only under relatively low distortion conditions). In two cases the simulated spectral decay is compared with the measured one (Figs. 7 and 8).

We measured 36 different conditions in addition to evaluating simulated data—a good basis for you to perform listening tests and investigate further. Note that the driver stage requirements increase as plate voltage rises. Be sure to check plate current for every tube change and adjust accordingly. Finally, in our opinion, the RCA operating condition is pretty close to being the best one.

Conclusion

From plate curve family data, using a

REFERENCES

1. D.C. Espley, "The Calculation of Harmonic Production in Thermionic Valves with Resistive Loads," *Proc. IRE*, Oct. 21, 1933.
2. C.E. Kilgour, "Graphical Analysis of Output Tube Performance," *Proc. IRE*, Jan. 19, 1931.
3. J. Millman, *Vacuum-tube and Semiconductor Electronics*, McGraw-Hill, 1958.
4. H.J. Reich, J.G. Salnik, and H.L. Krauss, *Theory and Applications of Active Devices*, Van Nostrand, 1966.

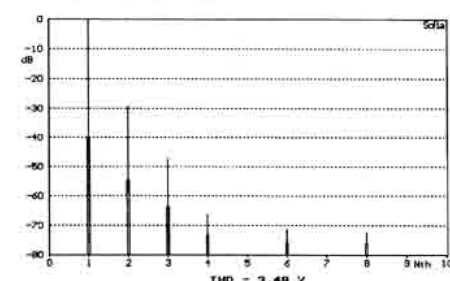


FIGURE 8C: C80 THD simulation.

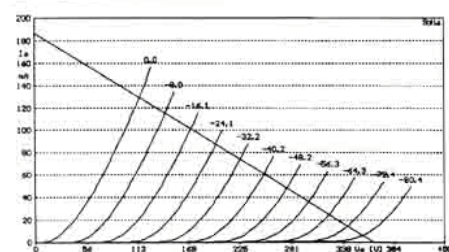


FIGURE 8A: C80 plate curves.

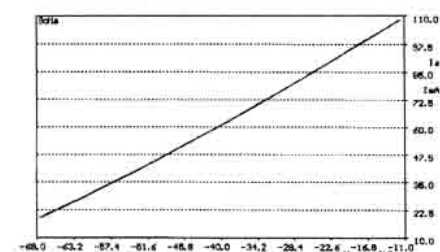


FIGURE 8B: C80 dynamic curve.

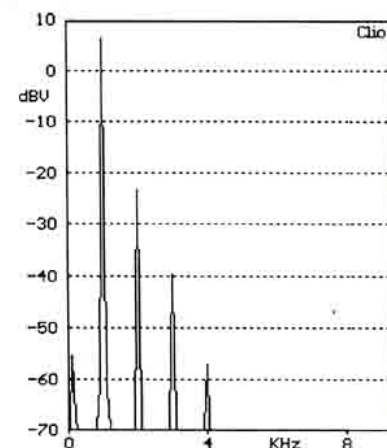


FIGURE 8D: C80 FFT analysis.

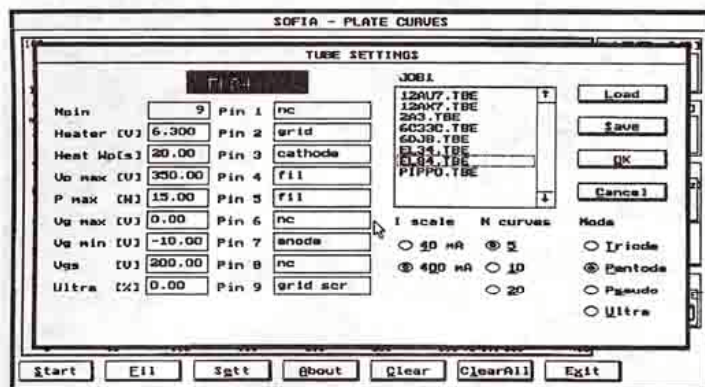


FIGURE 9A: EL84 directory.

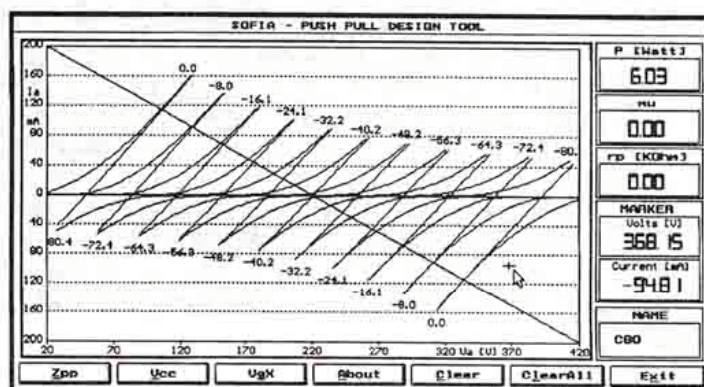


FIGURE 9B: Sample push-pull simulator control panel.

personal computer, you can reasonably predict the behavior of a tube SE output stage in terms of distortion and harmonic decay. As in every case, the results are

useful only with accurate input data. Evaluation of these results with a system other than an automatic one to obtain the data needs to be investigated.

Nevertheless, the process is quite similar to simulating loudspeaker performance from T/S parameters and single driver frequency response. ❖

Sofia: A World of Curves

We obtained the experimental data in this article with a TV-2B Electron Tube Tester and a prototype of the Sofia curve tracer. Sofia is a computer-controlled instrument to measure the electrical characteristics of almost any tube; the hardware is linked to an IBM or compatible PC via an RS-232 interface and accepts several different valves in its standard sockets.

Sofia system software controls all the functions of the hardware and manages the tube tests; it also features a tube directory containing all the manufacturer's mechanical data and electrical measurement limits. Sofia software helps the

design of tube-oriented electronics simulating the behavior of an electronic stage employing the measured tubes. It covers single-ended and push-pull situations. Future versions will include other topologies. *Figure 9* shows the tube directory dialogue box with the EL84 data and the push-pull simulator control panel with the composite characteristic curves of two output tubes.

Sofia is available from Audiomatica srl, via Faentina 244/g, 50133 Firenze, Italy, 39-55-575221, FAX 39-55-5000402, E-mail: audiomatica@mclink.it, WWW: <http://www.mclink.it/n/audiomat/audioeng.htm>.—MB/MJ

Glossary of Symbols

Vak DC	Plate-to-cathode operation voltage
Ia DC	Plate operation current (mA)
Vg DC	Grid-to-cathode operation voltage
Vak RMS	Plate AC voltage (measured)
Ia RMS	Plate AC current (measured)
Zp	Plate load (calculated)
P	Output power (calculated)
THD M	Distortion (measured)
THD S	Distortion (simulated)
E THD %	Simulated distortion error