The LW6-180 Amplifier

This author shares with us his design of a high-quality audio amp that produces 180W mono, bridge or balanced input, and 90 + 90W stereo.

BY SILVIO MANGINI

I designed this Class AB2 amplifier (*Photo 1*) around the union of the 18TU output transformer and the 6LW6 high-perveance beam power tube. The main specifications are reported in *Table 1* against IEC 268 standards.

THE 6LW6
The 6LW6 (and its 26V and 36V variants) are among the most powerful receiving tubes (*Photo 2*). Octal predecessor of the more famous 6LF6, the 6LW6 is a 40W beam tetrode in T14-7 size, originally intended as a horizontal-deflection amplifier that clearly surpasses the 6550A and KT88.

Horizontal-deflection output tubes with their astounding performance were not extensively used in audio amplifiers, because high perveance must be paid for from a lower than plate-screen-voltage rating.

In reading Schade,[1] every tube amateur should see what a masterpiece the 6L6 was in tube history (and to my

PHOTO 1: Completed amplifier.

knowledge there is no solid-state four-terminal equivalent). The KT88 is a tougher 6L6, something like two in parallel. But the 6LW6, 6LF6, or even the 30W 6JE6 (the MC-3500 output tube) behave like tougher KT88s.

Looking at the beam-power-tube golden age, a continuous trend to increased transconductance, while saving medium μ, is evident: 6L6, 6mA/V; 6550, 11 mA/V; 8417, 23mA/V. This was due to good engineering, the output stage needing to work on moderately low imped-ances (4–5kΩ) driven fairly by simple circuits.

Nevertheless, in the

'90's tube revival, good engineering practice may not be the main issue, as directly heated triode wizards well know. So a lot of cheap NOS horizontal output tubes that look like new audio output tubes, designed for a no-compromise amplifier, should have low impedance (i.e., high perveance) and a low amplification factor, after Champeix[2]:

$$r_p = \tfrac{2}{3} p^{-\tfrac{2}{3}} I_a^{-\tfrac{1}{3}} (\mu + 1)$$

where r_p = plate resistance,

p = perveance = cost $\times$ (S/d^2) = f(electrode geometry),

I_a = plate current,

S = electrode extension = f(effective cathode area), and

d = electrode distance.

Finally, since large cathode means high heater power, and the cathode-heater system is the primary tube-life factor, I believe research should be focused on cathode improvement.

MODIFIED ULTRALINEAR
Operation of low-impedance beam power tubes at levels exceeding the screen rat-
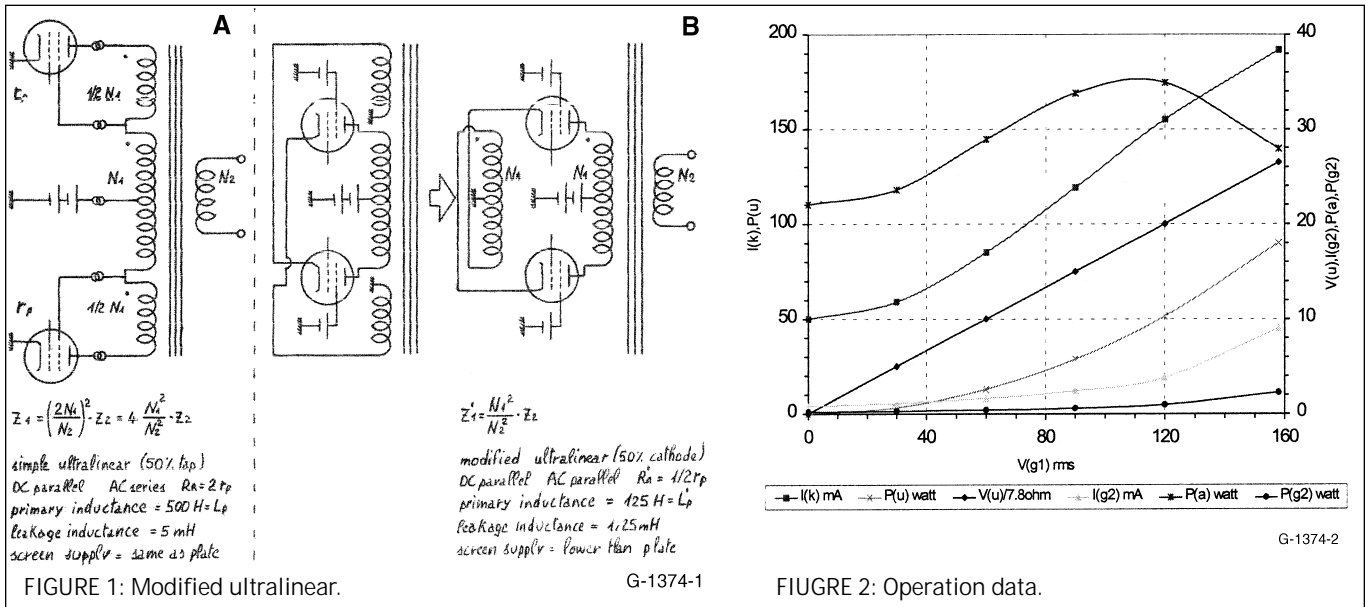
TABLE 1

SPECIFICATIONS	LW6-180	IEC 268
Frequency response	10Hz/50kHz-0.5dB	20Hz/20kHz ± 0.5dB
Total harmonic distortion	0.16% (1kHz), 0.4%(20Hz), 0.4%(20kHz)	<0.2% (20Hz/20kHz)
Intermodulation distortion	0.4% (50Hz, 7kHz 4:1)	<0.3% (idem)
Output power	2 × 90W	>2 × 10W
Absorbed power	300/580 VA	Not specified
S/N	>100dB (lin)	>80dB (lin)
Channel imbalance	<1dB (0 to −40dB)	<2dB (idem)
Channel separation	>50dB	>40dB

ABOUT THE AUTHOR
Silvio Mangini lives in Imperia, Italy. He built his first tube amp, a PP EL 84, in 1976. In the '80s, while studying Chemistry at Genoa University, he found Langford-Smith and other books and learned to design and wind OPT. Since 1989 he has worked as production manager in a small food and bulk pharmaceutical company. His hobbies are tubes and mountain hiking.

PHOTO 2: 40W beam power tubes.

FIGURE 1: Modified ultralinear.

G-1374-1

A

$$Z_4 = \left(\frac{2N_1}{N_2}\right)^2 \cdot Z_2 = 4\cdot\frac{N_1^2}{N_2^2}\cdot Z_2$$

simple ultralinear (50% tap)
DC parallel   AC series $R_a = 2\,r_p$
primary inductance = 500 H = L_p
leakage inductance = 5 mH
screen supply = same as plate

B

$$Z_4' = \frac{N_1^2}{N_2^2}\cdot Z_2$$

modified ultralinear (50% cathode)
DC parallel   AC parallel $R_a' = 1/2\,r_p$
primary inductance = 125 H = L_p'
leakage inductance = 1.25 mH
screen supply = lower than plate

FIUGRE 2: Operation data.

G-1374-2

Legend: I(k) mA · P(u) watt · V(u)/7.8ohm · I(g2) mA · P(a) watt · P(g2) watt

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TABLE 3
SUBSTITUTION CHART

ORIGINAL	EQUIVALENT	SUBSTITUTE
6LW6	26LW6, 36LW6	6LF6 (1), EL519 (1,2)
12AZ7A	12AZ7	6BZ7 (1)
7119	E182CC	12BH7 (1,2,3), 7044 (4)
5814A	E82CC	12AU7
E86C	EC86	6CM4, 6AB4½ 12AT7 (1.5)
5670	2C51	6DJ8 (1,3)
5881	6L6WGB	6L6GC (4)
E90F	6661	6BH6
EL82	6DY5	6CW5, 6BQ5
EC81	6R4	12AU7 (1,5)

(1) different basing
(2) lower ratings
(3) minor changes in circuit parameter/performance
(4) higher ratings
(5) major changes

from page 16

ings leads to loss of tube life. Both pentode and ultralinear connections can easily put severe stress on the screen grid in order to obtain full output from a given tube. This is why the plate-voltage rating in an ultralinear connection (supposedly equal to the screen-voltage rating) is generally lower than in a pentode connection (where you can use a lower supply for screen grids).

The inherently low screen-voltage rating of horizontal-deflection tubes led to some disagreeable inconveniences, such as a lot of tube abuse from one side, and an awful thing called "enhanced mode" from the other.

The elegant solution was pointed out by Crowhurst[3] and his modified ultralinear configuration: sharing the tube load between plate and cathode not only provides a great advantage in output-transformer design, but also makes it possible to operate screen grids at proper voltage.

You can investigate the modified ultralinear output circuit more thoroughly elsewhere; right now you only need to consider that it yields superior performance in all respects (distortion, susceptibility to load variation, output impedance) at the expense of high drive requirements.

TABLE 4
18TU SPECIFICATIONS

Nominal power/impedance	100W/8Ω
Turns ratio (whole primary to secondary)	16.74:1
Ultralinear ratio (cathode to whole primary)	0.43:1
Insertion loss	0.25dB
Primary current (per leg)	300mA
Primary inductance (whole primary)	575H
Leakage inductance (modified ultralinear)	1.2mH
Effective primary capacitance	150pF

Moreover, modified ultralinear configuration allows the screen grid to be supplied with correct voltage, stabilized if necessary, and act as a kind of DC control electrode, whereas the plate is the power electrode.

As you will see later, the LW6-180 (*Fig. 3*) is designed with a large margin below the maximum rating of every component; the output-tube screen grid has a full load dissipation of about 2.2W against the 7W design-maximum rating of the 6LW6 (*Fig. 2*).

LW6-180 SCHEMATIC
Figure 3 is the LW6-180 schematic, and *Table 2* is the parts list. It has some features in common with the Luxman A3000[4] and the McIntosh MC275,[5] but the former has triode output, while the latter has pentode. Modest examples of modified ultralinear are the Quad II[6] and the Audio Research D79[5], both having too

low a cathode load to be really different from pentode output.

Moreover, both the Luxman and McIntosh reach the high drive needed from the output stage by positive feedback applied to driver; in the LW6-180, I preferred the straightforward, i.e., a B+ high enough to fulfill the requirement directly.

Finally, this amplifier has a stabilized, soft-starting power supply and an original input amplifier that renders frequency bandwidth independent from volume setting, and provides a bridging option.

I used special quality tubes wherever possible; you can substitute these for current equivalents, no particular rating being necessary beyond superior quality. See substitution chart, *Table 3*.

OUTPUT STAGE
The output stage is the combination of output tubes and output transformer: none of these elements alone can provide anything. The 18TU is the output transformer I designed and wound for this amplifier in 1997. The basic specifications are listed in *Table 4*. The 18TU has H-class windings, Nomex® insulation, and a Terni M6 grain-oriented, annealed core.

In audio output-transformer design, the best balance between electro-magnetic properties of available materials and required performance is a matter of art. Beyond these, it is important to bear in mind that the right path in tube-audio power-amp design is performance, output transformer, output tubes; i.e., the transformer calls for certain tube characteristics, and not vice-versa. (By the way, this is the reason why OTL is ruled out for me: no transformer, no amp.)

A careful review of relevant literature

TABLE 2
PARTS LIST

Note: R100-C100-D100 = channel L
R200-C200-D200 = channel R
R300-C300-D300 = power supply
R400-C400 = input amplifier

RESISTORS

NUMBER	VALUE(Ω)	DESCRIPTION
R201	560	Metal film ¼W 1%
R202	46.4k	Metal film ¼W 1%
R203	470	Metal film ¼W 1%
R204	100	Metal film ¼W 1%
R205	9.9k	Metal film 18k & 22k ½W 1% in parallel
R206	2.48k	Metal film 3.9k & 6.8k ¼W 1% in parallel
R207	47	Metal film ¼W 1%
R208	44k	Metal oxide 2 × 22k 3W 5%
R209	1M	Metal film ¼W 1%
R210	19.5k	Metal film 2 × 39k ½W 1% parallel
R211	10k	Helitrim 20 turns ½W
R212	54k	Metal film 2 × 27k ½W 1%
R213	66k	Metal film 2 × 33k ½W 1%
R214, R215	3.3M	Metal film ½W 5%
R216, R217	330k	Metal film ½W 1%
R218	3.3k	Metal oxide 1W 5%
R219	22k	Metal film ½W 1%
R220, R221	60k	Metal oxide 27k & 33k 3W 5% in series
R222, R223	820k	Metal film ½W 1%
R224, R225	20k	Helitrim 20 turns ½W
R226, R227	22k	Metal oxide 3W 5%
R228, R229	12k	Metal oxide 3W 5%
R230, R231	1.2k	Metal film ¼W 1%
R232, R233	3.3k	Metal oxide 3W 5%
R234, R235	10	Metal film ¼W 1%
R236, R237	100	Metal film ¼W 1%
R238	10	Wirewound 6W 5%
R301	200(cold)	Ntc thermistor, 4 × 50Ω 2A, in series (about 8Ω hot)
R302	8(cold)	Ntc thermistor, 8Ω 4A (about 0.2Ω hot)
R303	220	Wirewound 5.5W 5%
R304	22	Wirewound 5.5W 5%
R305	270k	Metal film ½W 1%
R306	510k	Metal film ½W 1%
R307–R310	12k	Metal film ¼W 1%
R311, R313	270	Metal film ¼W 1%
R312, R314	330	Metal film ¼W 1%
R315	6.8	Metal oxide 1W 5%
R316	200(cold)	Ntc thermistor, same as R301
R317–R320	270k	Metal film ½W 1%
R321	100k	Metal film ½W 1%
R322	30k	Metal oxide 2 × 15k 2W 5%
R323	270	Metal film ½W 1%
R324	330k	Metal film ½W 1%
R325	50k	Helitrim 20 turns ½W
R326	150k	Metal film ½W 1%
R327	8.2k	Metal film ¼W 1%
R328	100k	Metal film ½W 1%
R329	5.6k	Metal film ¼W 1%
R330	470(cold)	Ntc thermistor, 1W (about 20Ω hot)
R331	220	Wirewound 5.5W 5%
R332, R333	360k	Metal film 2 × 180k ½W 1%
R334	8.2k	Wirewound 15W 10%
R335	10	Metal film ¼W 1%
R336	270	Metal film ¼W 1%
R337	220	Metal oxide 2W 5%
R338	100k	Metal film ½W 1%
R339	12k	Metal oxide 2W 5%
R340	100k	Metal film ½W 1%
R341	5.6k	Metal film ¼W 1%
R342	8.2k	Metal film ¼W 1%
R343	220k	Metal film ½W 1%
R344	820	Metal film ¼W 1%
R345	50k	Helitrim 20 turns ½W
R346	390k	Metal film ½W 1%
R347	470	Metal film ¼W 1%
R348	1.8k	Metal film ¼W 1%
R401, R402	50k	Plastic film 2 × 50k Log (sect. Aligned −1dB from 0 to −40dB)
R403	22k	Metal film ½W 1%
R404	2.7k	Metal film ¼W 1%
R405	39k	Metal film ½W 1%
R406	390k	Metal film ¼W 1%
R407	6.8M	Metal film ¼W 5%
R408	22k	Metal film ½W 1%
R409	2.2k	Metal film ¼W 1%
R410	2.7k	Metal film ¼W 1%
R411	390k	Metal film ¼W 1%
R412	39k	Metal film ½W 1%

CAPACITORS

NUMBER	VALUE	DESCRIPTION
C201	100µF	Electrolytic 250V 20%
C202	470pF	Silver mica 500V 1%
C203	201pF	Silver mica 500V 1%
C204	360pF	Silver mica 500V 1%
C205	0.47µF	Polyester 630V 10%
C206, C207	0.044µF	Polypropylene 630V 10%, 2 × 0.022 in parallel
C208	33pF	Silver mica 500V 2%
C209	100µF	Electrolytic 100V 20%
C210, C211	0.22µF	Polypropylene 1000V 10%
C212, C213	10µF	Polyester 250V 10%
C214	0.1µF	Polyester 630V 10%
C301	0.01µF	Polypropylene 1500V 10%
C302	100µF	Electrolytic 100V 20%
C303–C312	0.01µF	Polypropylene 1000V 10%
C313, C314	100µF	Electrolytic 400V 20% LL
C315, C316	470µ	Electrolytic 400V −10 + 30% LL
C317	0.1µF	Polypropylene 1000V 10%
C318, C319	1000µF	Electrolytic 385V −10 + 30%
C320	100µF	Electrolytic 400V 20%
C321	1µF	Polyester 250V 10%
C322	0.1µF	Polyester 400V 10%
C323	22µF	Electrolytic 450V 20%
C324–C326	100µF	Electrolytic 450V 20% LL
C327	0.01µF	Polypropylene 1500V 10%
C328–C331	100µF	Electrolytic 400V 20% LL
C332	1µF	Polyester 250V 10%
C333	0.1µF	Polyester 400V 10%
C334, C335	22µF	Electrolytic 450V 20%
C401–C403	0.1µF	Polyester 400V 10%
C404, C405	1µF	Polyester 400V 10%
C406	91pF	Silver mica 500V 1%

DIODES

NUMBER	VOLTAGE	DESCRIPTION
D201	150	Zener 5W (1N5383B)
D301, D302	400	Rectifier 1A (1N4004)
D303	120	Zener 5W (1N5380B)
D304–D307	1200	Rectifier 3A (BY255)
D308–D313	1000	Rectifier 1A (1N4007)
D314	–	LED, red-green
D315, D316	150	Zener 5W (1N5383B)
D317	82	Zener 5W (1N5375B)
D318–D324	476	Zener, 7 × (68V 5W) (1N5373B)
D325, D326	82	Zener 5W (1N5375B)

MISCELLANEOUS

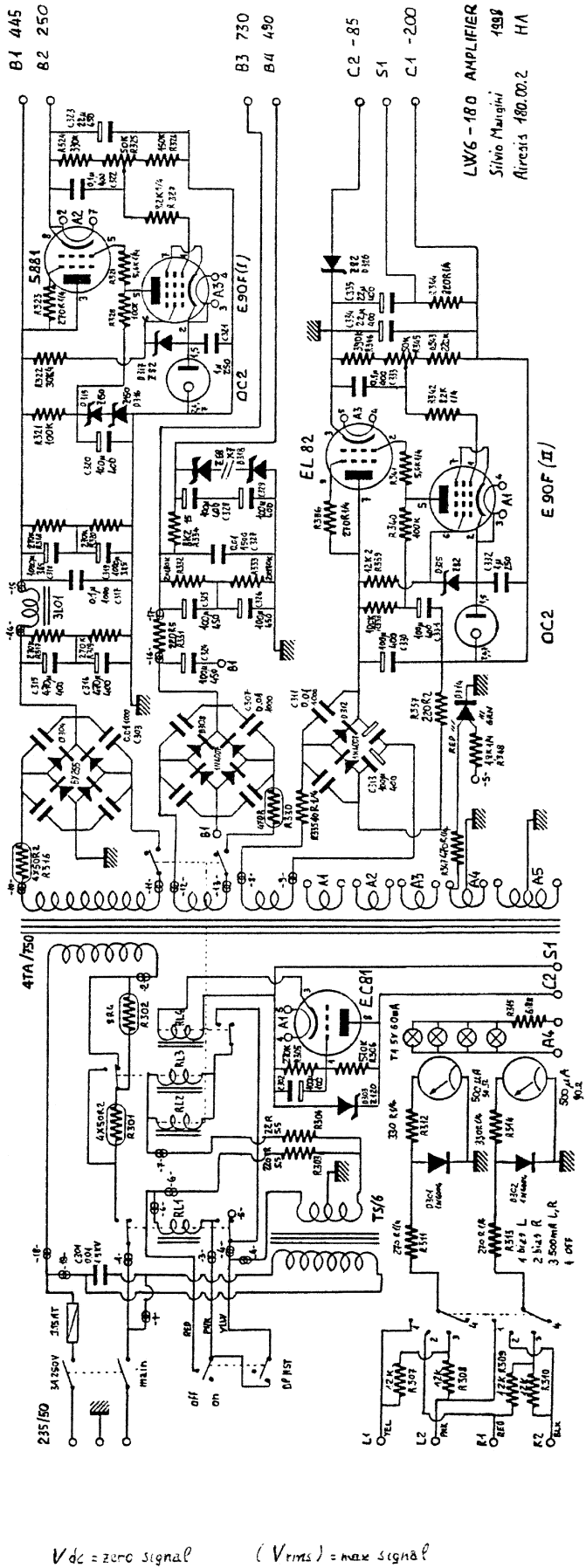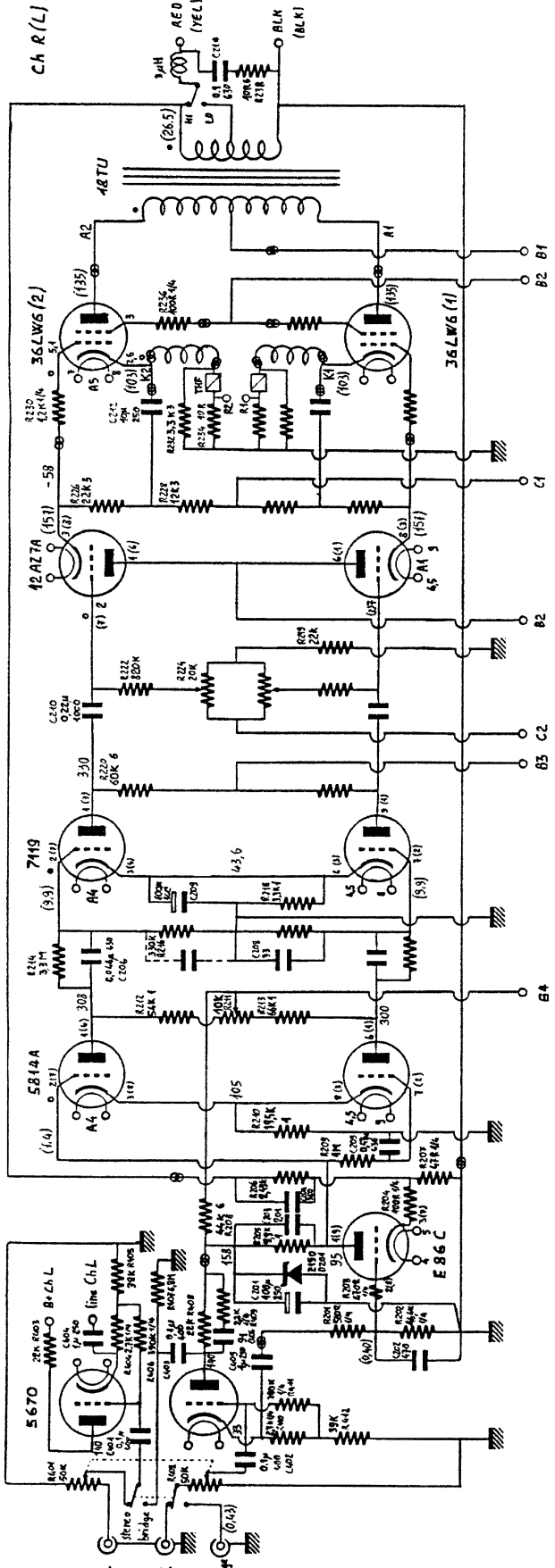| ITEM	NAME	DESCRIPTION
RL1	Mains relay	DPDT 8A 250V (440V max) (24V AC 1VA coil)
RL2	HT relay	DPDT (same as RL1)
RL3	Soft-start relay	SPDT 12A 250V (24V AC 1VA coil)
RL4	Servo relay	SPDT 10A 250V (48V DC 0.5W coil)
TS/6	St-by transformer	Potted 230/12 + 12V 6VA (RS 201-7022)
–	Meters	2 × Mc 500µA 90Ω DC (E.T.E.I.ltd)
–	Meter lamps	4 × T1 bulb, 5V 60mA 40.000hr (RS 587-664)
–	Main transformer	See Table 6 (Dr. Mangini model 4TA)
–	Lf choke	1H 0.8A 8.4Ω (Dr. Mangini model 3L)
–	Rf choke	2 × 3µH 9A 6mΩ (RS 213-1752)
THF	Autoreset fuse	4 × 0.4A (RS 183-9562)
–	Output transformer	See Table 4 (2 × Dr. Mangini transformer model 18TU)

FIGURE 3: Schematic diagram.

can confirm this statement; here I'll make reference only to Crowhurst.[7] That great work is devoted to analyzing the merits of triode or pentode operation of output tubes, but while it encouraged me in my studies that led to the 18TU, it also emphasizes that output circuits of better quality always call maximum performance from the transformer.

It is the output *circuit* that matters, not the single component, tube, or transformer; but this last is by far the most critical, because you cannot obtain from a given circuit more than the transformer can do, while a given iron-core transformer may be driven by a different choice of output tubes. Of course, in making this choice, some characteristics the transformer calls for are preferable and with respect to these, some tubes will be better than others.

From various works on output transformers—Macfadyen,[8] Cohen,[9] and Flanagan[10]—it is clear that two main things are requested "from the transformer's point of view" in order to get the best performance: low source impedance and no DC magnetization. The latter definitely does away with the single-ended circuit. The former (also meaning low impedance ratio, which is very desirable) is necessary to keep low ferromagnetic distortion and to get wide frequency response.

DISTORTION AND FREQUENCY RESPONSE

As for distortion, according to Partridge[11] you have

$$THD = V_h/V_f = 5.54 S_h l R_a/N^2 A f (1 - R_a/4Z_f)$$
$$\cong cost \times R_a/f L_p$$

where V_h = harmonic voltage appearing across the primary,

V_f = fundamental voltage across the primary,

S_h = distortion coefficient of the magnetic material,

l = magnetic path length,

N = number of primary turns,

R_a = equivalent resistance in series with the primary $\cong$ source impedance,

A = cross-sectional area of the core,

f = fundamental frequency, and

Z_f = primary impedance at fundamental frequency $\approx 2\pi f L_p$.

As to frequency response, since high source impedance needs high inductance and inductance (and therefore leakage inductance) is proportional to the square of the turns number, the lower the source impedance, the higher the upper limit of useful bandwidth. Moreover, modified ultralinear gives a further reduction of effective source impedance. For instance, consider the case of an equal number of turns in plate and cathode windings: if you connect the two halves of one primary in series with the other, you have the normal ultralinear with 50% taps (*Fig. 1a*). Now take a value for the transformer's coupling factor, say 100,000 (quite a good iron); as is well known[12] the primary-to-leakage inductance ratio (L_p/l_s) is a function only of the shape of the core and coils and of the permeability of the core, so if $L_p = 500H$, then $l_s = 5mH$.

If you connect the primaries in parallel, which is the case of modified ultralinear—being both plate- and cathode-winding

center-tap grounded—you have half the turns number, or one-fourth of the primary and leakage inductance, 125H and 1.25mH (*Fig. 1b*). The low-frequency response is unaffected, since nothing is changed in the source impedance-to-primary inductance ratio, but on the high spectrum side, the resonance frequency

$$fr = \tfrac{1}{2}\pi(l_s C_s)^{\frac{1}{2}}$$

is halved, and the stray capacitance C_s is held constant (indeed, in a good design, the chance of C_s reduction, offered by a modified-ultralinear shared load, certainly will not be lost). Needless to say, the higher the resonance frequency, the wider the frequency response and/or feedback factor.

LW6-180 DETAILS

The LW6-180 has output transformers matching the 8Ω load to 2.2k primary impedance (nominal primary impedance of cathode and plate windings in series) with 0.25dB loss, i.e., 0.94 efficiency.

The audio power of 100W on a 2.2kΩ load is easily obtainable by four 6550s in ultralinear parallel push-pull, Class AB1, with efficiency in the region of 0.50 and less than 2% harmonic distortion. This is the classic 100W amplifier. Two 6550As and even two KT88s are not enough, even if working on more than a doubled load, say 5kΩ; in fact, these tubes were designed for amplifiers of up to 100W, but this level was never reached in hi-fi equipment, such as the MC 275, HK Citation II, and so on, rather only in PA and guitar amps. The same applies to four 6L6GCs or EL34s, unless you approach dangerously maximum ratings.

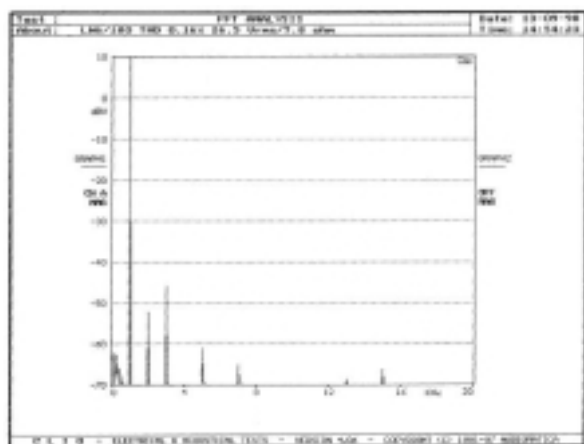Through my extensive experimentation in the last two years—and as McIntosh has demonstrated with the MC3500

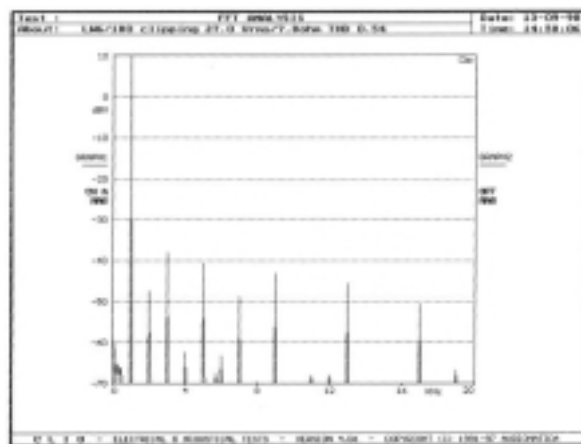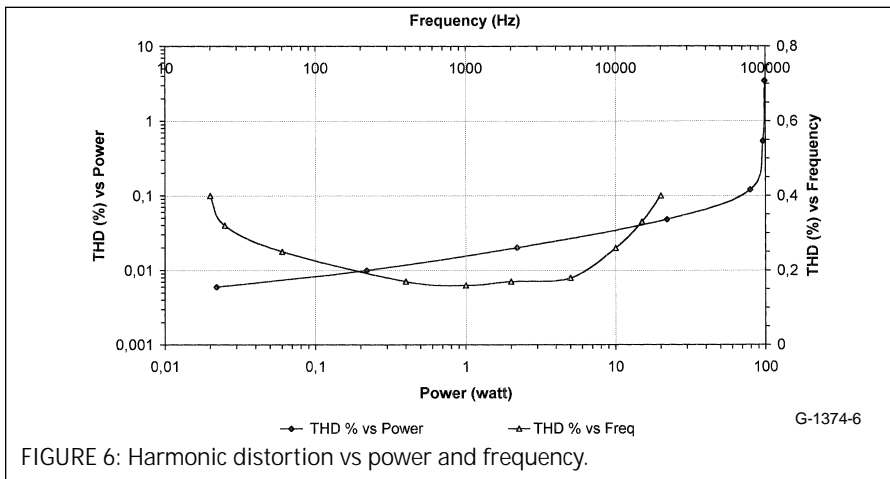

FIGURE 4: Distortion spectrum at full power. G-1374-4

FIGURE 5: Distortion spectrum at clipping. G-1374-5

FIGURE 6: Harmonic distortion vs power and frequency.

—high-perveance beam power tubes of the 35–40W plate-dissipation class do the job. Intriguingly, when multiple-service ratings are reported in tube handbooks about the same tube type, the deflection-amplifier service always has lower ratings than the Class A service (6V6, 6CZ5, EL86). Moreover, the 40W plate structure of the 6LW6 is 20% wider than the 42W plate of the 6550A, while its cathode has twice the emitting area (and 400mA maximum DC current) with a 16.7W heater, in contrast with the 10W heater and 190mA of the 6550A cathode.

Not only do TV sweep tubes do the job, they are also very linear. I will not now produce the average plate characteristics of the 6LW6; a good curve tracer is not available in my lab, and I believe it would take me too much time.

When I obtained the first lot of 6LW6s in early 1996, I started immediately to breadboard and soon found good amplifying qualities. I was already aware of horizontal-deflection tube linearity, since it is necessary in TV sets. Skeptics can compare available graphs from the literature (e.g., the 6DQ5 with the 6L6 in RC-19[13]). Then my working conditions were optimized with the aid of a distortion meter (HP 331A) and a spectrum analyzer (CLIO).[14] During 1996 the first LW6 amplifier was built, the 180.00.1. It had four 6LW6s, a choke-input power supply, a 12BH7 driver without a cathode follower, and 4TU03 output transformers. The 4TU03 was the 100W version of the 4TU, my first cathode load transformer.

I had wound the 4TU in 1992, thinking to use a pair of 8417s. Like the 4TU, the 4TU03 has a 0.28 ultralinear ratio and 7mH of leakage inductance that causes harmonic distortion to rise at high frequency. Some kind of feedback (4TU > 6LW6 > better transformer) is at the origin of the 18TU. Then I did a lot of work in developing the power supply and driver stages.

The operation data of the LW6-180 modified ultralinear output stage is summarized in *Table 5*, *Fig. 2* and *Figs. 4–7*. Of course, the data applies to the whole amplifier. *Figure 2* is a plot of typical operation characteristics. *Figure 6* is a plot of harmonic distortion versus power and frequency at full power, while *Figs. 4* and *5* show the distortion spectrum at maximum power and after clipping, respectively. *Figure 7* is a plot of output power and distortion versus load impedance. *Photo 3* displays the square-wave response at 10kHz.

DRIVER AND PREAMPLIFIER
Continuing along the design line, after the output transformer and output tubes, comes the driver with severe requirements: high voltage drive (160V RMS) with low distortion and good dynamic head. Moreover, the driver must have low output impedance in order to obtain full output from the final stage in the grid-current source region, and it cannot be RC-coupled, otherwise the overload characteristic assumes the "catastrophic" behavior pointed out by Crowhurst as trigger effect.[15]

Having tested several high-dynamic circuits with a spectrum analyzer, among them the totem pole and μ-follower, I concluded the best drive is the straight Class A, medium-μ triode, with cathode follower direct-coupled to the final control grids. High output level simply means high B+ supply, nothing else. Because the push-pull drive for Class AB2 must not only be sufficient, but also perfectly balanced, I worked hard to achieve good balance (otherwise output tubes are not driven equally in push pull, one side underworking while the other is overdriven). I don't worry too much about imbalance with tube-parameter drift (tube aging), because the cathode-follower buffer has inherent full feedback, and the voltage-amplifier driver is a Class A, high-quality tube, very conservatively underrun in counterphase stage. An aged tube, if aging impairs characteristics, must be replaced. I take a lot of care with initial balance.

A good balanced signal comes from a good phase inverter. I discarded the Van Scoyoc cross-coupled phase inverter because it doesn't work at high level, the concertina because it lacks gain and is difficult to adjust at high frequency, and

TABLE 5
MODIFIED ULTRALINEAR OUTPUT STAGE
OPERATION DATA

Plate-supply voltage, zero signal	E(b), 0	445V DC
Plate-supply voltage, max signal	E(b), max	412V DC
Screen-grid supply, zero; max	E(g2), 0; max	250; 250V DC
Screen-grid current, zero; max	I(g2), 0; max	0.8; 9mA
Cathode current, zero; max	I(k), 0; max	50; 192mA
Bias voltage	E(g1), 0	−58V DC
Maximum-signal plate voltage	V(a), max	135V RMS
Maximum-signal cathode voltage	V(k), max	103V RMS
Maximum-signal grid voltage	V(g1), max	157V RMS
Plate dissipation, zero; max	P(a), 0; max	22; 26.5W
Output power, both channel driven	P(u)	90W RMS
Output voltage/load resistance	V(u)/R₁	26.5V RMS/7.8Ω
Total harmonic distortion	THD	0.16% @ 90W
Overall feedback factor	Nfb	21dB
Frequency bandwith, −3dB	Fr	1Hz–100kHz
Overload	–	Smooth, stable
Stability	–	Unconditioned
Signal to noise ratio	S/N	100dB(lin)
Voltage gain (sensitivity)	G	35.8dB (0.43V RMS)
Damping factor (8Ω)	DF	24

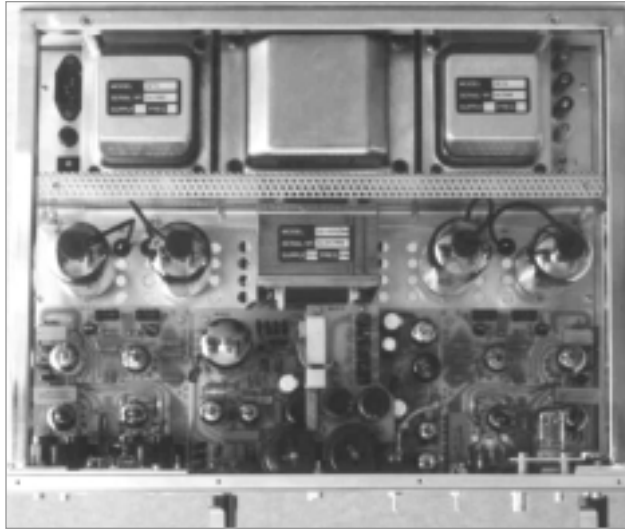

PHOTO 3: 10kHz square-wave response.
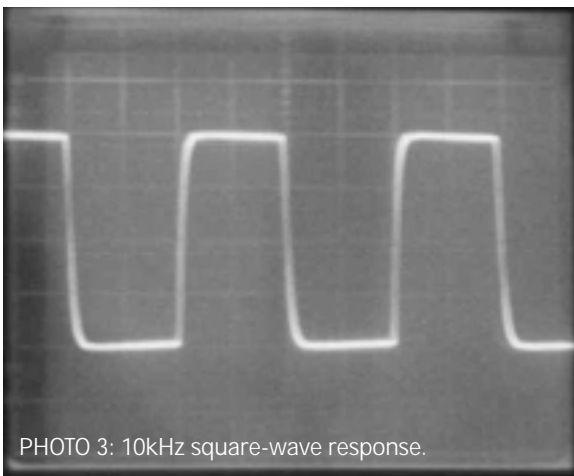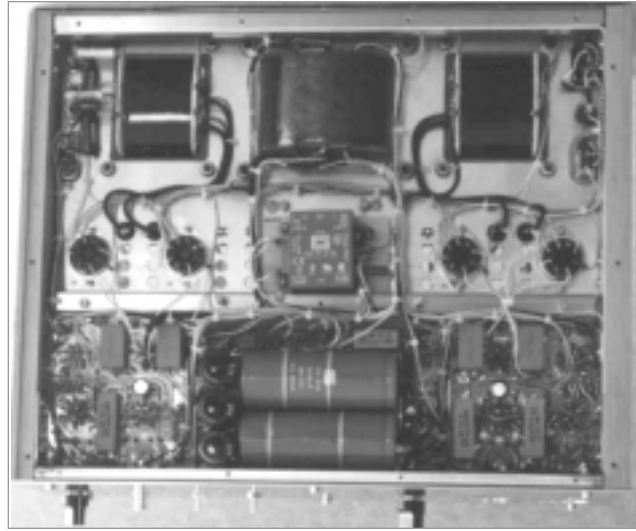
PHOTO 4: Top view.

PHOTO 5: Bottom view.

the differential amplifier because it is difficult to reconcile with feedback or it needs balanced input. At the end, the McIntosh topology proved to be the best, with some variations: I redesigned the Schmitt phase inverter and the input amplifier parameters, inverting high-frequency behavior (discussed later) and inserting the helitrim in the 5814 plate circuit to set AC balance while monitoring performance with the spectrum analyzer.

In fact, the Schmitt phase inverter is provided with an adjustable plate load (R111, R211) that you can regulate on the finished amplifier by observing the distortion display on the spectrum analyzer or the cathode current of the output tubes (L1–L2 and R1–R2 test points) with two DC millivoltmeters. After presetting the output tubes' quiescent bias (adjust R124–R125 and R224–R225 for the same idle current [50mA] on both tube pairs), apply a 1kHz sine wave at, say, a 10V RMS output level (which involves a cathode-current increase to about 80mA) and adjust R111 and R211 until dynamic balance is achieved. This corresponds to equality in output-tube currents and minimum distortion. Then check the balance at the higher level.

High-frequency dynamic balance needs fine tuning of stray capacitances, which is achieved by inserting small capacitors C108 and C208 across one side of the phase inverter load—the side used depends on the specific layout as well as final capacitor value. In my LW6-180 final driver PCBs I found 33pF shunting R117 and R217 was necessary, whereas in the prototype only 12pF on the opposite side achieved perfect balance. Trial and error in monitoring cathode cur-

rents is not difficult with a bit of experience, but remember you are dealing with lethal voltages!

(As an example, I obtained balance between my 36LW6 push-pull pairs within 2% cathode current at any frequency up to 50kHz. If you wish a pictorial image of the importance of high-frequency balance, look at Lissajous patterns of your amplifier: if the ellipse is not perfect at 20kHz or 50kHz, forget a nice THD figure.)

Finally, regarding frequency-band extremes, the low side is conventional, having two main time constants besides the output transformer, one of which is stepped. The high side was designed to fit 18TU performance by setting the 5814 stage as the narrow one, while all the other stages have wide bandwidth (staggered from 120kHz to 3MHz). This explains the low plate load of the first stage, which also benefits signal-to-noise ratio.

INPUT AMPLIFIER

The two channels of the LW6-180 amplifier share a twin-triode input amplifier devoted to source decoupling. The 5670 cathode follower has high input impedance, so the LW6-180's frequency response is independent of the volume setting, a feature generally missing in most amplifiers, as observed by Crowhurst.[16]

Moreover, the input amplifier allows bridged mono operation, drawing an inverted signal from one triode plate. Its performance is bandwidth 400kHz, hum plus noise better than 100dB.

POWER SUPPLY

The LW6-180 needs somewhat more than "heater and B+." The two channels require four positive HT voltages (B1–B4), two

negative (C1, C2), and three heater supplies (A1, A4, A5). A2 is the separate 6V3 supply for the 5881 heater (+250), while A3 is dedicated to E90F(I) and EL82 heaters. This winding could have been omitted by strapping heaters to A4 (6V3 CT grounded bus), but this solution would bring 75V DC across V_{hk} of E90F(I). This is rated at 100V, and 75 is well within the limit, but a separate heater winding is conservative. Finally, A1 is the separate supply for the E90F(II) heater (−125); it also feeds the two 12AZ7s and the EC81.

Moreover, the 4TA/750 is clearly a custom transformer, and when I was designing and winding the prototype, it was better for me to distribute heater power in different windings, rather than manage A4 with thicker wire. In fact, the 4TA/750 has a high window-filling ratio

TABLE 6
NOMINAL 4TA WINDING VOLTAGE AND CURRENT

WINDING	VOLTAGE(V)	CURRENT(A)
Primary	235	3.2
Main HT	350	1.4
Extra HT	230	0.1
Bias	106	0.1
Heater A1	6.3	1.3
Heater A2	6.3	1
Heater A3	6.3	1
Heater A4	6.3 CT	2.9
Heater A5	36 CT	1.8

TABLE 7
I_A/ V_A CHARACTERISTICS

	E(G1)	E(G2)	E(A)	I(A)
Operating point	−41V	400V	400V	40mA
Operating point + 10%	−45V	440V	440V	46mA
Only E(g1) stabilized	−41V	440V	440V	58mA
E(g1) & E(g2) stabilized	−41V	400V	440V	40.8mA

PHOTO 6: Side view.

FIGURE 7: Power and distortion vs load impedance.

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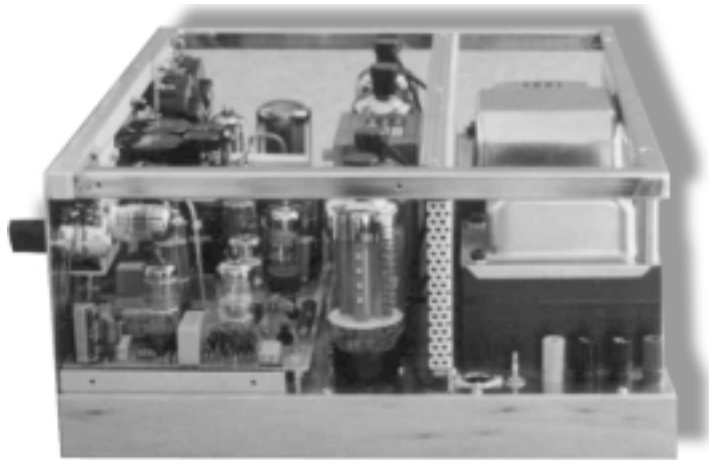
(0.86 instead of the usual 0.70) and very low magnetic flux density (1.0T). Other features are: power rating, 750VA; efficiency, 0.93; insulation, class H; a core transformer, 80mm-tall EI, with a 45mm-wide stack, Terni M6T35 low-loss oriented-grain silicon steel. *Table 6* shows the nominal voltage and current. Winding data is available, although I'm afraid building such a transformer would require a lot of skill.

B1 (the main B+) is the DC power source for the output tubes. It must be as stiff as possible; i.e., have good regulation. Since the output stage is Class AB2, there is a large variation between no-signal and full-output current—more than 3:1. B1 is 412V DC at maximum rated output, and it rises to 445V in quiescent condition. This good regulation comes from the careful choice of rectifier and filter parameters.

B1 also feeds B2, the 5881 regulated screen supply. In this way, there is no risk that the output tubes will have their screens powered without B+ on the plates. Should the plate supply fail or RL2 open, B2 goes to zero.

The regulator circuit is classic but features as a bonus the soft B+ start for output tubes. When RL2 closes and B1 and B2 are energized, the B2 voltage gently ramps up to +250, the regulator being driven by the time constant of capacitor (C320) charge in the E90F(I) anode circuit.

As previously described, among the advantages of the modified ultralinear configuration is that the screen grid acts as a DC control electrode, with all the positive features (efficiency, low input capacitance) of separation of DC control from AC, and without the inherent disadvantages of pentodes (distortion, high output impedance, screen overload).

In fact, feeding the control grid (bias)

and screen grid (accelerating grid) from stabilized sources provides close control of output-tube operating conditions, almost as good as though total stabilization (e.g., plate supply) were adopted (this not being feasible for efficiency reasons). As an example, operating conditions from the I_a/V_a characteristics, both triode and pentode connected, with correct E(g2) as a parameter, are displayed in *Table 7* (from 6L6GC data[17]).

The data in *Table 7* shows that a 10% increase in operating voltages (as a consequence of mains variation) leads to a 15% plate-current increase, whereas grid stabilization leads only to a 2% increase of plate current. The phenomenon is more relevant with high-perveance tubes.

STARTING SEQUENCE
Having examined the DC control action of the screen grid, it is now clear how it may be useful in the soft start of output tubes. I will now review this together with other features of the starting sequence.
1. Closing the main switch enables the amp to start. The "service" transformer (TS/6) is energized, and the line LED turns red.
2. Pulling up the starting switch (non-stable) energizes RL1, which is now self-excited and stays on (green LED) unless a) the starting switch is pulled down to intentionally turn off the amp, or b) a mains blackout happens. In this event the amp is switched off to avoid the risk of a hot switching transient. The mains power goes down, RL1 opens, and the amp remains off. A new starting sequence must be performed.

RL1 energizes the main power transformer via a 200Ω (cold) thermistor. This is designed to limit the cold heaters' current inrush. In fact, now only the heaters and bias power transformer secondaries are working. So as the heaters gently warm up,

the bias and "negative HT" (C1) slowly reach operating conditions, while other secondaries, i.e., the "positive HT" (B1–B4), are held off by the retarder circuit.

This circuit is formed by the RC cell (R306-C302) on the EC81 grid (whose time constant is actually 45 seconds) that drives the two power relays (RL2, RL3) via the servo relay RL4 on its cathode. The retarder circuit is powered by the bias circuit. In this way, the positive HT is subjected to bias presence and is disconnected in case of bias failure.

After the 45 seconds, with the heaters having nearly reached operating temperature, RL2 and RL3 close. The latter shorts the starting thermistor (R301), the resistance of which decreased from 200 to about 10Ω during warm-up, and opens the operating thermistor (R302, 8.4Ω cold). This is seen $(N2/N1)^2$ times in series with the main transformer's impedance and the R316 200Ω (cold) on the B1 secondary.

These act together as the main B+ surge damper, which softens the inrush current charging the main capacitor bank. The thermal time constants of the thermistors are a few seconds, so while positive HTs gently reach their operating voltages, output tubes are slowly "activated" by their screens ramping from zero to +250. You can monitor the soft-starting sequence with output-tube current meters:
1. Main switch on; only red LED on; meter lights off.
2. Starting switch up; red LED turns to green, meters brighten; zero current; 45-second delay begins to count down.
3. After the delay, a small click indicates relay operation, and within a few seconds, the meter currents grow gently from zero to 50mA (bias preset)—no overshoot, no speaker "bump," no full-scale jump. The amplifier is operating. You may open the volume control (be
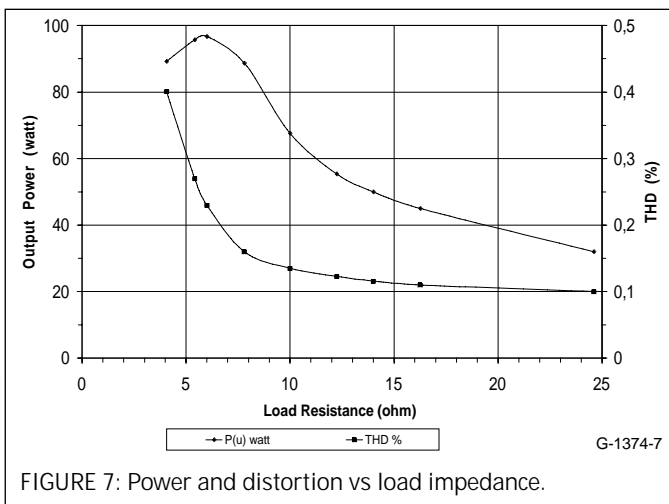
careful of your ears) after setting the meter switch to off or to 500mA L or R. (During musical operation, the meters show the transition from Class A to AB.)

B3 and B4 feed driver stages and they are obtained by superimposing a floating 300V DC on B1, which yields the 730V (nonregulated) for the 7119 drivers (B3), while B4 (B+ for input amp, preamp, and inverter) is derived from B3 via RC filtering and zener stabilization. This requires some waste of power (from 730 to 490), but yields a very low ripple. B3 being formed with B1 and submitted to RL2 constitutes a protection for the 7119 and other tubes. Their HT is applied gently after heater warm-up, so the plate voltage never exceeds the rating limit of each tube.

THE PROTOTYPE
Top and bottom views are shown in *Photos 4* and *5*. The LW6-180 is built on a tough stainless-steel chassis, with solid walnut sides and a 2mm-thick polished stainless-steel front panel. The overall dimensions (420mm × 330mm × 160mm) are quite small. Regarding power, the full-load input is 580VA, 400 of which is converted into heat. The amplifier is designed for convection cooling, and suitable air circulation is provided by careful thermal layout. Of course, convection channels must not be clogged nor impaired by sur-rounding devices; otherwise, up to three 80 × 80 × 25 low-noise cooling fans can be accommodated under cover to provide cool operation.

Plate-current meters with their mode selectors, on/off and stereo/bridge switches, the bridge BNC input, and the volume control are located on the front panel (*Photo 1*), while input (DIN), output (heavy-duty binding posts), and mains socket (VDE) are located in hollow side panels (*Photo 6*).

Transformers, filter choke, and output tubes are directly mounted on the chassis, and most other components are in three main PCBs. Left and right amplifiers are electrically identical, each board being a mirror picture of the other. At the center is the power-supply board, which is quite complicated, a result of superimposing three boards in order to save space.

The amplifier is hardwired with Teflon® or fiberglass/Mylar® suitable gauge wire; 36LW6 plate caps have thick, high-temperature silicon wire; and the 5670 input amplifier is mounted near Clarostat volume control without PCB. ❖

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