Mad Katy

A 125W per channel KT88 Amplifier – Part 1

Meet Miss Katy, a stereo tube amp featuring KT88s, who seems to possess the perfect temperament to faithfully reproduce music.

By Dennis Colin

Mad Katy is a 250W (stereo or monoblock) tube amplifier on a 17″ × 22″ chassis; weight is about 70 lbs (**Photos 1-6**). It has excellent sonic fidelity, transparency, and solidness up to clipping level, achieved by circuit features designed to minimize high-order distortion, reactive load sensitivity, and compressive gain modulations. Ruggedness and reliability are such that it can be used as a musical instrument amp.

To provide 250 sustained watts (1% THD) from a 70 lb. tube amp required the high efficiency of push-pull Class AB topology (and the power-to-weight efficiency of toroidal transformers). However, the potential anomalies of Class AB operation have been avoided by means of some of the circuit features (**Fig. 1**).


PHOTO 1: *Mad Katy.*


PHOTO 2: Front view.


PHOTO 3: Left side.


PHOTO 4: Top view.


PHOTO 5: Rear view.

TOPOLOGY AND DESIGN FEATURES

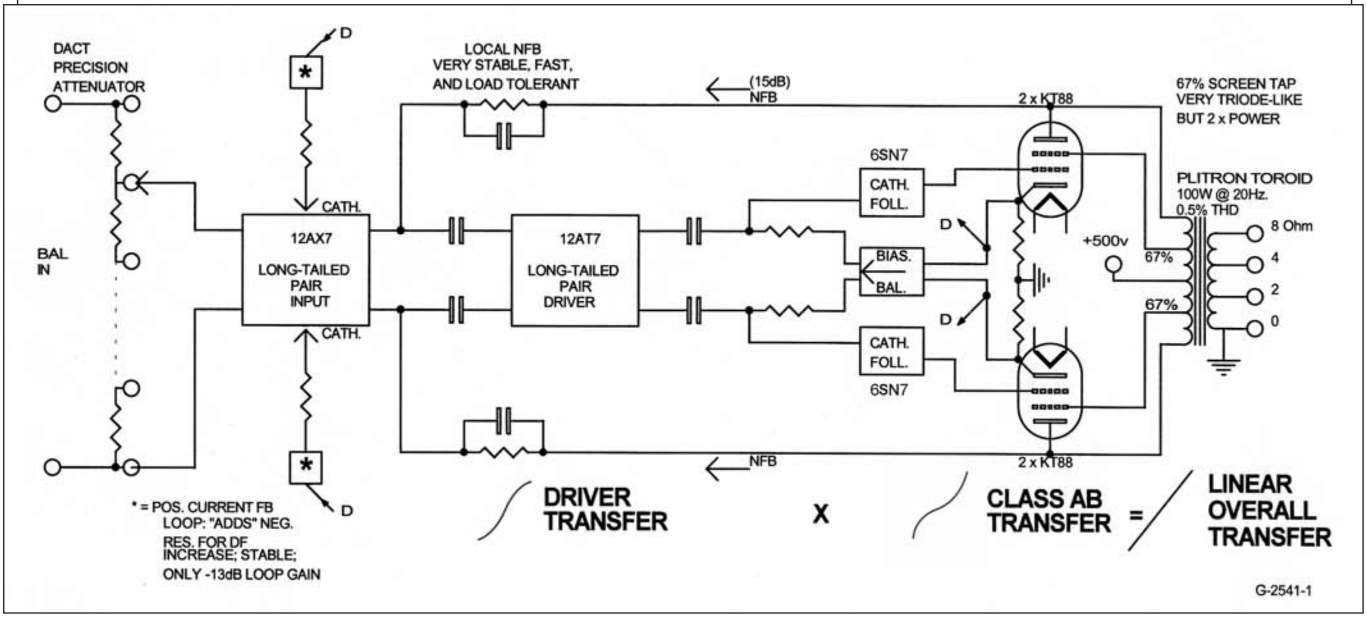
1. Forward (non-feedback) linearizing of output stage transfer function with complementary-transfer driver (**Figs. 1** and **2**).

2. "Partial Triode" KT88 mode: 67% screen tapping maintains triode-like characteristics (**Fig. 3**), but with twice triode power output.

3. Negative feedback (from KT88 plates to 12AT7 driver input) includes neither the output transformer nor the 12AX7 input stage. With phase shift thereby minimized, stability and transient response are uncompromised (**Fig. 4**), and distortion is minimized with (real-world) reactive loads.

4. 6SN7 cathode-follower driver buffers are direct-coupled to the KT88 grids. The low-impedance drive without coupling caps provides wide bandwidth

FIGURE 1: Topology. Forward linearizing: 0.27% THD, 1kHz, 100W, mostly 2nd and 3rd harmonic.



and smooth, anomaly-free overdrive onset and recovery (**Fig. 5**).

5. Fully-balanced (differential) circuitry throughout provides 113dB "A" weighted dynamic range.

6. Damping factor is adjustable from 4, through essentially infinity, to a small negative output resistance.

PHOTO 6: Right input.

PHOTO 7: JJ/Tesla. KT88.

FIGURE 2: Voltage transfer functions. Source = 1kHz linear triangle wave, level for ±28.3V (200W Pk, 4Ω), 67W average (100W if sine).

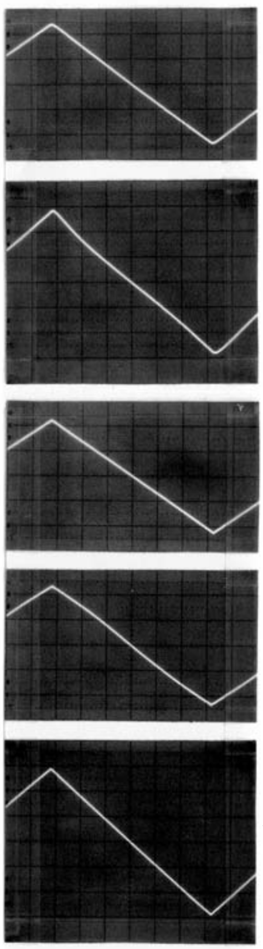
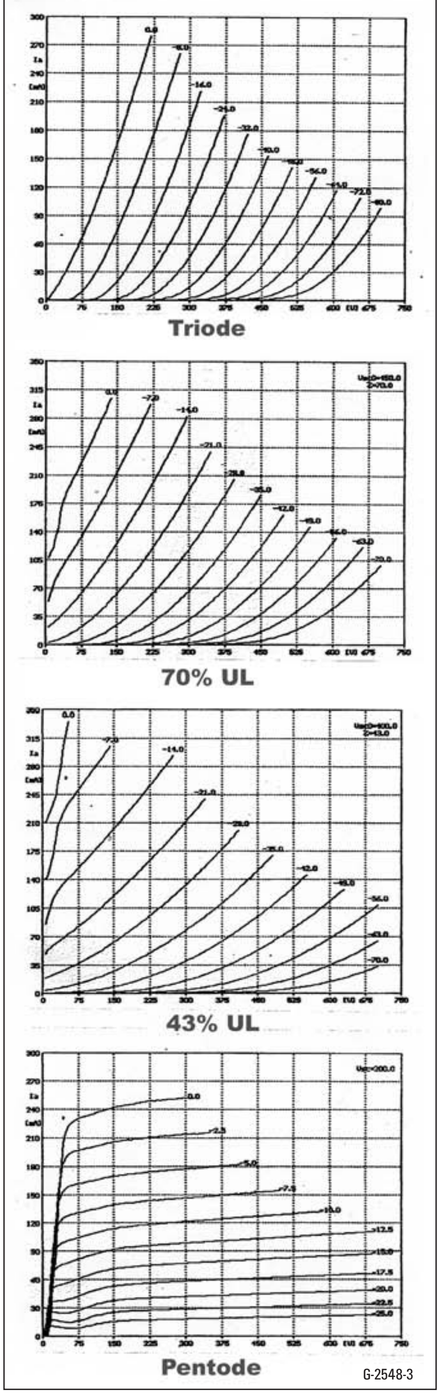


FIGURE 3: KT88 characteristics.



This is provided by a local current feedback loop that doesn't compromise stability or transient clarity.

7. Non-feedback bias stabilizer: This, along with extremely solid power supplies, keeps high-power signal compression to less than 0.1dB (**Fig. 6**).

8. Servo DC transformer balance circuitry; no adjustment needed, no saturation even with one output tube inoperative.

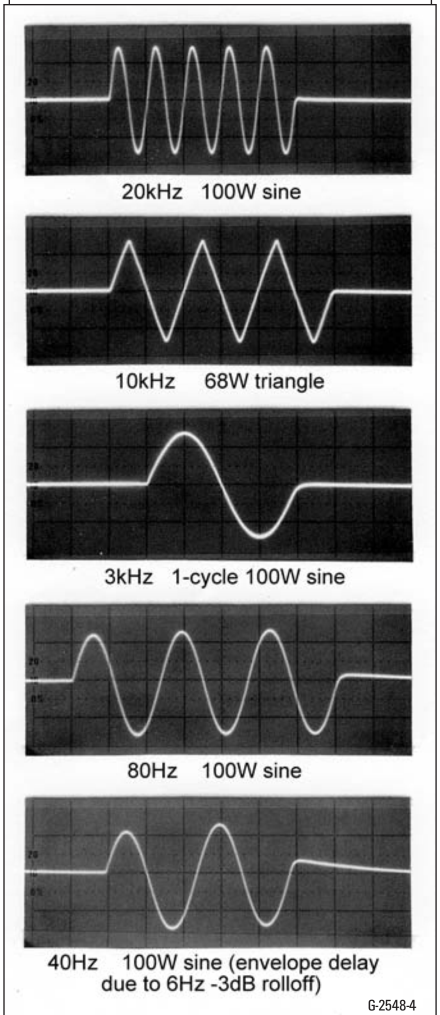
9. Plitron toroidal output transformers deliver 112W per channel at 20Hz, 1% THD, and a BW –1dB of 12.5Hz to 39kHz (**Fig. 13**).

10. Ruggedness: output can be shorted during sustained 10dB overdrive, without blowing even a fuse.

ADDITIONAL FEATURES

1. Switchable RCA or balanced XLR inputs.
2. DACT precision step attenuators.
3. Polarity-inverting switches, useful for bridged monoblock.
4. Bias-indicating LED comparators.
5. Six power supply fuses with corresponding status LEDs.
6. Ultra-clean power supplies using five toroidal transformers. All tube heaters and HV are surge-limited. Power-on HV has 20 second delay. HV FET switch provides "soft" (inaudible) standby/active switching.
7. AC line is fed through an EMI filter receptacle, inrush current limiter, and voltage transient suppressor.

FIGURE 4: Tone bursts. 200W peak, average power stated. 4Ω load.
20kHz 100W sine • 10kHz 68W triangle
3kHz 1-cycle 100W sine • 80Hz 100W sine
40Hz 100W sine (envelope delay due to 6Hz -3dB rolloff)



Overall, the amplifier (schematics, **Figs. 7**, **12**, **17 (in part 2)**) appears complex, with a fairly large parts count. However, the audio path is straightforward and relatively simple, as it should be. Much of the complexity is due to the "housekeeping functions" and six very solid power supply voltages (four regulated).

Materials cost was about $2300. In the interest of economy, you could use the basic amp with simpler supplies and without the "housekeeping" functions. You could use 6550 output tubes, but

I strongly recommend JJ/Tesla KT88s (**Photo 7**). They provided 10% more power and lower distortion than KT88s from another high-quality manufacturer.

Table 1 summarizes the measured performance data.

AMPLIFIER CIRCUIT

Refer to the amp circuit in **Fig. 7**. RCA or balanced XLR inputs are selected through S1; C1 removes any DC offsets that would cause attenuator transients. The signal is then applied to AT1, a DACT precision step attenuator. R6 is to (a) taper this for about 1dB steps near maximum gain (attenuator itself is 2dB/step down to –34dB), and (b) lower the maximum output R seen by the 12AX7 input tube V1; this is to reduce variation of Miller effect loading. R7 is to balance the average (over attenuation range) source R to the two polarity input triodes, to maximize CMRR.

S2 is a polarity inverting switch, facilitating use as a 250W bridged monoblock.

V1 is a long-tailed pair with excellent output balance and input CMRR, because the cathodes are supplied from a high (68k) resistance, R14, and the –200V bias supply; compared to the maximum ±1.2V input swing, this is a nearly ideal (and linear resistive) current source. Zeners D1, 2 provide a path for this current in standby (where the –200V stays on) to prevent the grids from conducting significantly. (The –200V stays on to prevent output tube bias surges and thumps when switching out of standby.)

Note that the negative feedback (NFB1, NFB 2) from the KT88 plates is fed (through R18, 19, C6, 7; R28, 29, C10, 11) to the 12AX7 plates. This lowers the load resistance seen by the 12AX7 to about 7kΩ each plate, a very low value. However, only about 9V p-p is needed for full output; distortion is very low. Furthermore, what little there is, is symmetrical and compressive, adding slightly to the intentional compression of the 12AT7 driver; this is used to linearize the KT88 Class AB output, which has a complementary expansion.

C8/R25 and C9/R26 form the dominant LF rolloff pole, at around 28Hz open loop. This ensures LF stability, while the 15dB of NFB results in an overall LF –3dB rolloff of 6Hz.

R16 and C4 provide a small amount of HF flatness compensation. P1 is used for fine gain match of the two channels.

DRIVER

This is a 12AT7 long-tailed pair (V2). D3 provides the same function as D1, 2; a zener is not needed here because the grids are biased at about +5V from the symmetry trimpot P2, so the cathodes are at about +9.5V DC, keeping D3 off except in standby.

The 12AT7 driver has a smoothly compressive limiting curve that very well compensates the expanding transfer function of the output stage (**Fig. 2**).

V3 (6SN7 GTB) is a dual cathode follower, DC coupled to the KT88 grids. This provides the advantages of

TABLE 1: MEASURED PERFORMANCE DATA

Amplifier data 4Ω load 117V 60Hz AC line
Maximum power (3% THD)
1kHz: 142W (1 channel), 268W (combined or monoblock), 155W per channel tone burst
20Hz: 112W per channel 20kHz: 90W per channel
THD %

	1W	10W	25W	50W	100W	IMD, 200Hz + 10kHz, 4:1
20Hz	0.05	0.14	0.22	0.33	0.50	0.7%, 100W
1kHz	0.03	0.08	0.12	0.18	0.27	0.2%, 70W
5kHz	0.05	0.16	0.22	0.51	0.90	1.0%, 70W, 4Ω //2μF load
10kHz	0.09	0.32	0.55	1.1	1.7	0.09%, 30W
20kHz	0.18	0.65	1.4	2.4	3.3	

Frequency response: -1dB BW = 12.5Hz – 39kHz; -3dB BW = 6Hz – 65kHz.
Rise time (10–90%): 4.0μs at 10W, 5.3μs at 185W (square-wave power).
Damping factor: >20, 40Hz – 10kHz; 13 at 20Hz; 9 at 20kHz.
Sensitivity: 0.775V RMS for 100W, 1.36V peak for clipping.
Input impedance: 76kΩ (RCA), 16.4kΩ (XLR); C_{IN} = 115pF (all at max gain).
Noise output: 0.053mV RMS, 20Hz – 20kHz unweighted.
Hum output: 0.31mV RMS
"A" weighted signal/noise + hum: 113dB re 125W
Channel separation: 86dB (20Hz – 10kHz), 75dB (20kHz)
Balanced input common-mode rejection: 33dB, 20Hz – 20kHz
AC power consumption:
154W, standby 398W, active, no signal
677W, 2 × 100W sine
915W, 2 × 200W square
500W, typ. music at full power
AC line input range: 110–125V RMS, 60Hz

FIGURE 5: Bridged monoblock 1kHz 2-cycle burst. 8Ω load 10% duty 20V/div. 0.5vS/div. AC line = 116V RMS 60Hz ≈ 1% THD/234W sine average • 1.5dB overdrive/300W average power • 10dB overdrive/452W average power 528W peak power

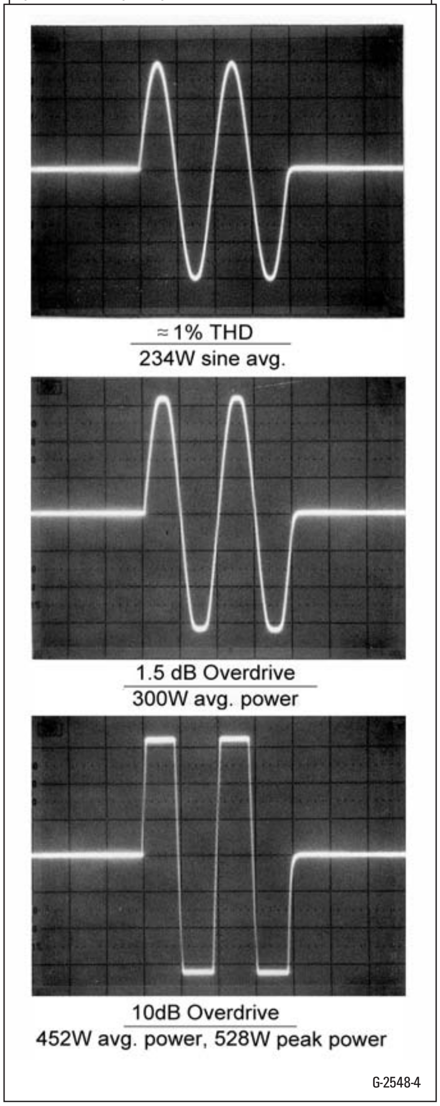
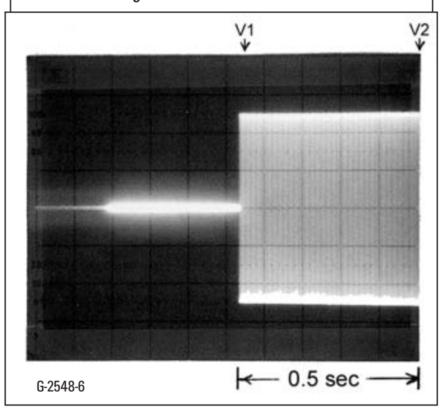


FIGURE 6: Amplitude stability of full-power signal.
1kHz step onset 100W sine 4Ω load v2/v1 = 1.0113. change, 0 to 0.5sec = 1.13% = 0.098dB Amplitude change, 0.5 – 60sec (not shown) = -0.0174dB, both channels, driven, 100W each Amplitude stability, onset of 2 × 100W signal to 60sec later = ±0.058dB.



low output impedance, wide bandwidth (500kHz), and transient-free overdrive and recovery. Bias (servo-balanced) is supplied to V3 through R33, 34.

OUTPUT STAGE

The paralleled push-pull KT88s (V4, 5, 6, 7) in Class AB ultralinear (UL) appear conventional except for some strange-looking things near the transformer primary. But first, the cathodes have 10Ω 1% current-sensing resistors, serving several functions: (a) bias sensing

FIGURE 7: Amplifier schematic.

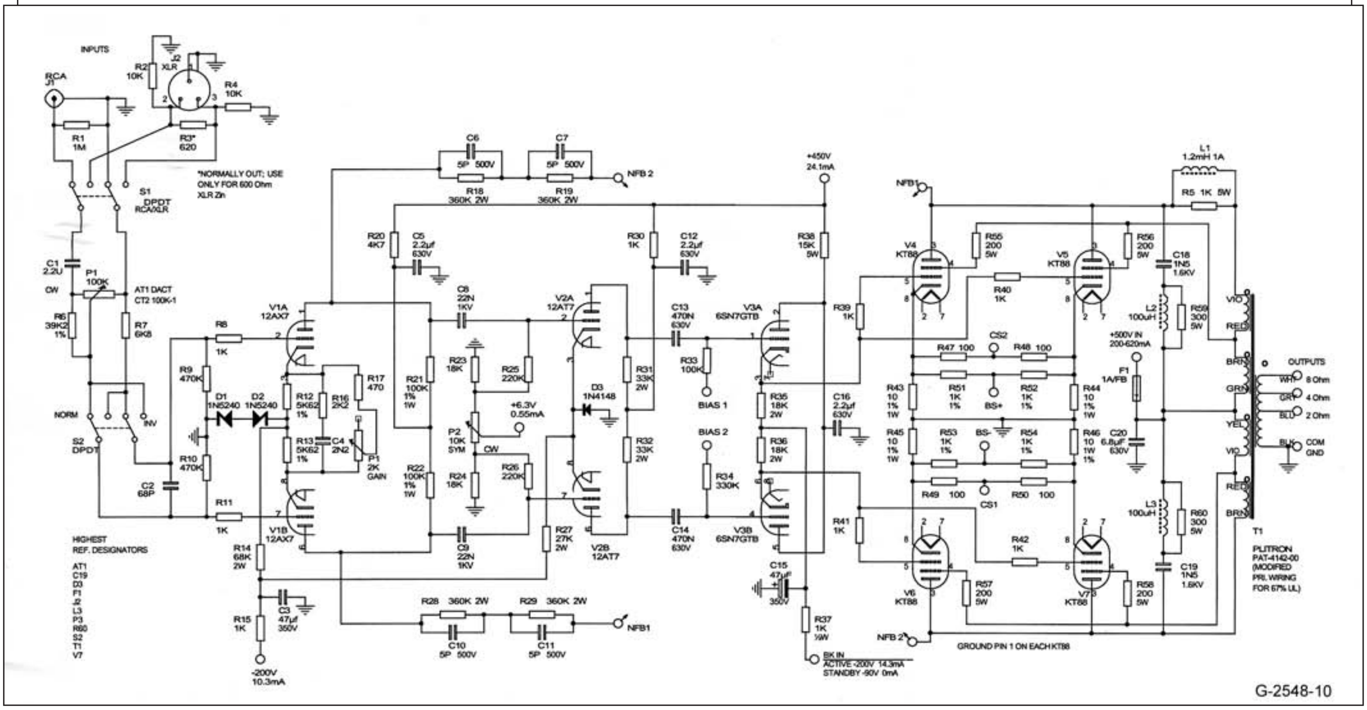


FIGURE 8: Push-pull Class AB load lines.

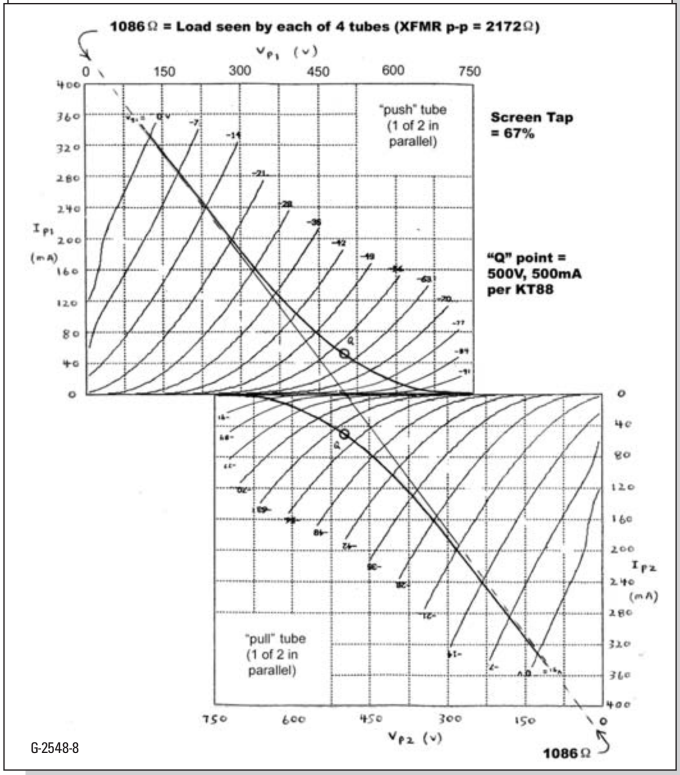


FIGURE 9: PAT-4142-00 transformer primary rewiring. Good match for four KT88s, HV = +500V, bias = 50mA/tube, AB1. Primary windings must be in below order for best leakage inductance symmetry (if using 66 2/3% screens).

Primary winding	*Relative turns ratio*	*DCR*
1	1.0000	34.5Ω
2	0.5000	15.8Ω
3	0.5000	15.4Ω
4	1.0000	29.9Ω

Measured on s/n 200202

Turns ratio, full primary to: Blk-blu = 31.38 Blk-gry = 22.24 Blk=wht = 15.81

Approximate interwinding C: any primary pair 100pF Total primary to sec 440pF.

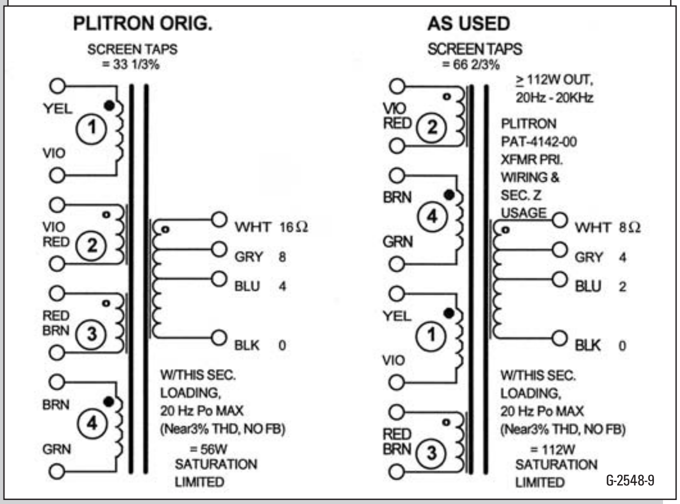
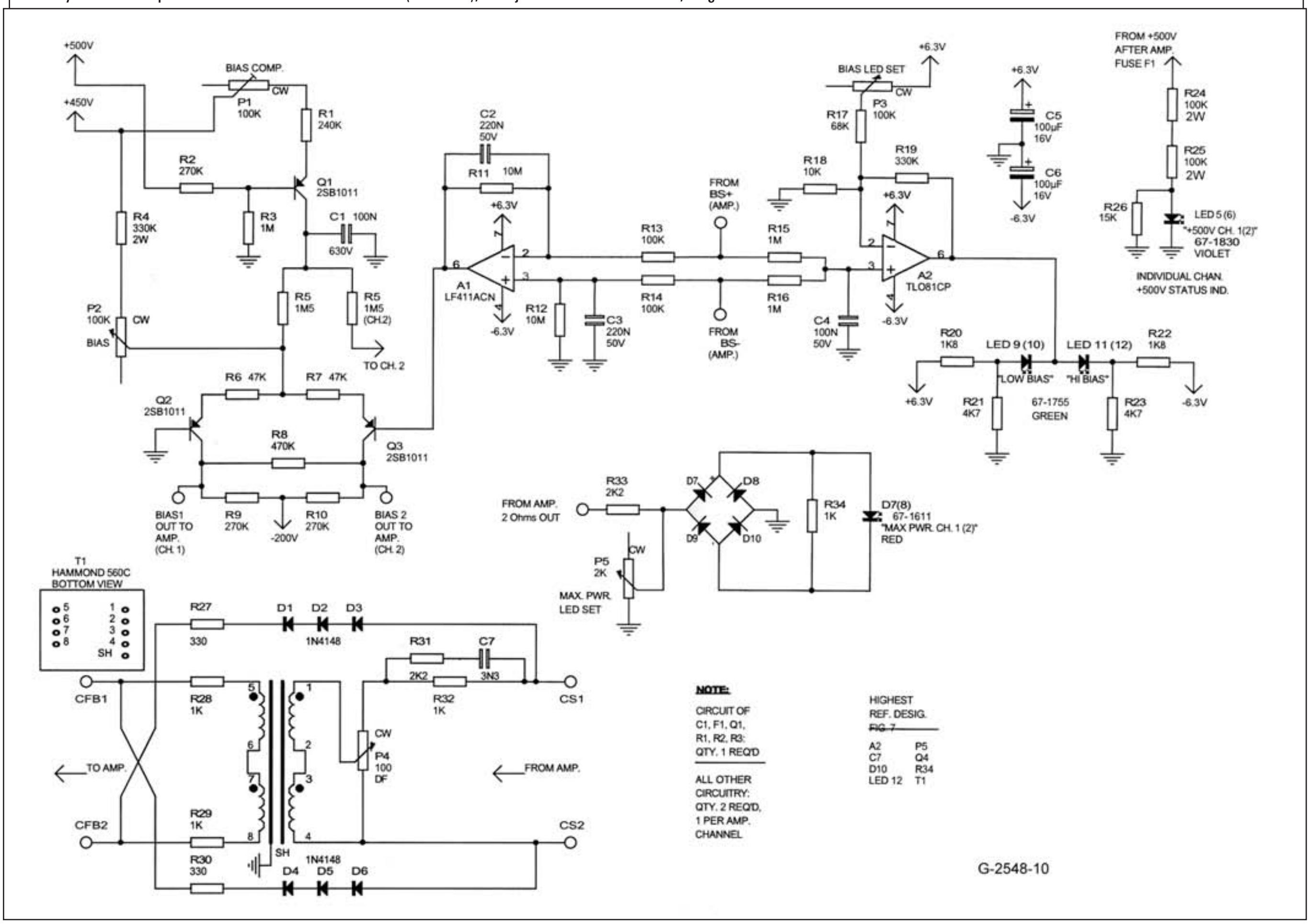


FIGURE 10: Bias, servo balance, current FB, and status LED schematic.

Note: initial pot settings: P1 = 48k (w-cw) • P2 = Full ccw • P3 = 44k (w – cw) Damping factor current feedback loop and output current limiter. Note: Set P4 (w – ccw) to 40Ω initially. Maximum power ind. Note: with P5 ≈ 575Ω (w – ccw), LED just on at 75W sine out, bright at 100W.



(at the "BS+" and "BS-" points); these drive the servo-balance circuit, indicating LEDs, and chassis-top banana jacks; then (b) points labeled "CS1" and "CS2" drive a current feedback (CFB) circuit (on **Fig. 10** with the servo balance), returned to the 12AX7 cathodes (points "CFB1" and CFB2"); this is the damping factor compensator.

Finally, the "CS1," "CS2" points also feed the normally-off current-limiting feedback diodes shown in **Fig. 10** in the event of output shorting or overloading.

Figure 8 shows the composite push-pull load line sensed by each one of the four output tubes.

OUTPUT TRANSFORMER

C18, L2, R59 and C19, L3, R60 were necessary to damp out a strong transformer impedance peak around 450kHz. This had raised mayhem with the NFB loop, until the above components resulted in a wideband smooth capacitive impedance curve. Note that this could not have been avoided by changing to the usual NFB feed from the secondary, because this transformer has significant spurious transmission to beyond 5MHz—Plitron states a wide bandwidth, but it's a little *too* wideband! No problem, fixed it.

The second unusual step was to rewire the primary (**Fig. 9**) for 67% UL screen taps, to have near triode-like operation (more linear, lower output Z) without the severe power penalty of pure triode operation. As shipped, the primary has three leads that are each a pair with ends soldered together; unsoldering these revealed four isolated windings, which I re-configured as shown in **Fig. 9**. Note: don't cut these leads to shorten them; each lead is a number of fine enameled magnet wires—difficult to strip.

Following is an explanation of L1 (with its damping resistor R5): above about 50W at 20kHz, about 5% asymmetry was observed. Reversing push/pull tubes made no difference. Then I measured leakage inductance of each primary half to sec. (by shorting sec.)—one primary half showed 1.0mH, the other 2.2mH. So I added the difference, a 1.2mH 1A inductor (L1) in series with the lower –L primary plate lead. This greatly improved 20kHz symmetry.

TRANSFORMER LOW FREQUENCY CAPABILITY

The transformer is designed for 80W and 4kΩ p-p to 4, 8, 16Ω. The half power LF frequency is stated as 14Hz (40W). Now when saturation-limited, the maximum output follows a 6dB/octave slope (the flux limit allows a given voltage per turn per Hz, so maximum power drops to ¼ for an octave lowering of frequency); then at 20Hz the maximum power would be about 80W (measured 56W maximum in-circuit). I reasoned that, staying within the flux-voltage limit, I could halve the load impedance (hence the 2-4-8Ω outputs), drawing twice the load current, and achieve nearly double the LF power limit. ("Nearly" because now the winding resistances would have double the losses.) Also, now the primary Z pp would match the 2kΩ load of 4-KT88s in 67% UL.

Norman Woo of Plitron thought my ½Z idea should be OK; he's right: the amp can deliver about 115W at 20Hz, and at 100W the THD is only 0.5%. I tried, for curiosity, a Hammond 1650T, rated at 120W with –1dB (95W) at

30Hz. Not only was 20Hz power much lower than with the Plitron toroid, but distortion was much higher even at power levels well below the maximum.

BIAS COMPENSATOR

Bias magnitude is compensated against supply variations, but is not servo (feedback) regulated; this would be complicated in a Class AB stage because the average cathode current increases nonlinearly with signal power. On the other hand, DC bias *imbalance* is a differential signal like the audio itself; think of it as a "zero-frequency audio" error signal. Therefore, you can apply a linear negative FB (servo) loop to reduce DC imbalance to an arbitrarily low level.

Joseph Norwood Still points out (2/00 *GA*, p. 62) that if both plate and negative bias supplies are unregulated, then as AC line voltage changes, these supplies will track together, tending to maintain reasonably constant tube bias current. But here the negative bias supply is regulated while the plate supply is not. In addition, I wanted the bias current stabilized against plate supply "sag" due to high power loading, to eliminate signal compression.

Referring to **Fig. 10**, Q1 compares the unregulated 500V plate supply with the regulated 450V supply (as a reference), and its collector current increases as the 500V decreases, whether from load sagging or AC line drop. P1 adjusts the amount of this compensation current.

This Q1 current, divided to the two amp channels by the R5 1.5m resistors, is added to the current from the bias-setting pot P2; the summed current feeds one emitter of the diff-amp Q2-Q3. C1, in conjunction with the two channels' 1.5m resistors, filters the compensation signal above 2Hz.

The diff-amp outputs "BIAS 1" and "BIAS 2" drive the amplifier's 6SN7 grids through R33 and R34 (**Fig. 7**). Back to **Fig. 7**, if the output of A1 is zero, the two bias outputs are (ideally) equal. An error voltage from A1 serves to differentially unbalance the two bias outputs as needed.

SERVO BALANCE

Straightforward in principle, the design of the negative FB loop is not trivial; the applicable parameters of loop-gain rolloff and phase margin must be adequate to ensure stability. This must be maintained (and was tested) from zero signal to overdrive, but I also made sure that no instability would occur even with output transformer saturation (which normally won't occur, but I induced with an overdriven 10Hz signal). Furthermore, the servo-balance loop, which attenuates DC and infrasonic frequencies, introduces a LF rolloff (highpass pole/zero response) into the overall amplifier NFB loop.

All of this made the design of the simple-looking circuit rather "interesting." But it works very well, and has proven to be completely stable with a variety of abusive test signals, including highly overdriven bass-heavy music.

The cathode-current sensing voltages "BS+" and "BS-" from the amp are fed to A1, a diff-amp with DC gain of 100. C2 and C3 provide a LF rolloff of 0.07Hz

FIGURE 11: Positive current FB loop generating negative output resistance. A voltage (V2) proportional to load current (io) increases amplifier drive (va) when load impedance (ZL) decreases, compensating voltage drop across amplifier output resistance (ra).

$V_a = v_1 + i_o r_{sc}$ • $V_o = v_a - i_o r_a$ • $V_0 = v_1 + i_o (r_{sc} - r_a)$ • R_o = output resistance seen by load • $R_o = -dv_0/di_o = r_a - r_{sc}$

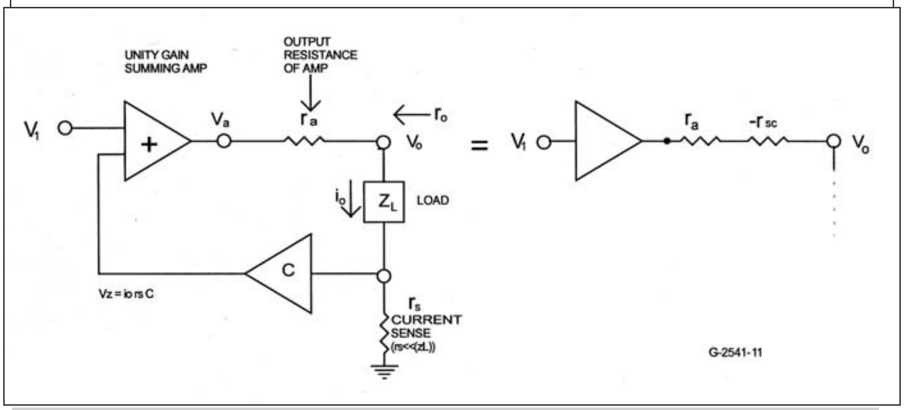


FIGURE 12: Panel component locations. Top, front panel; bottom, rear panel

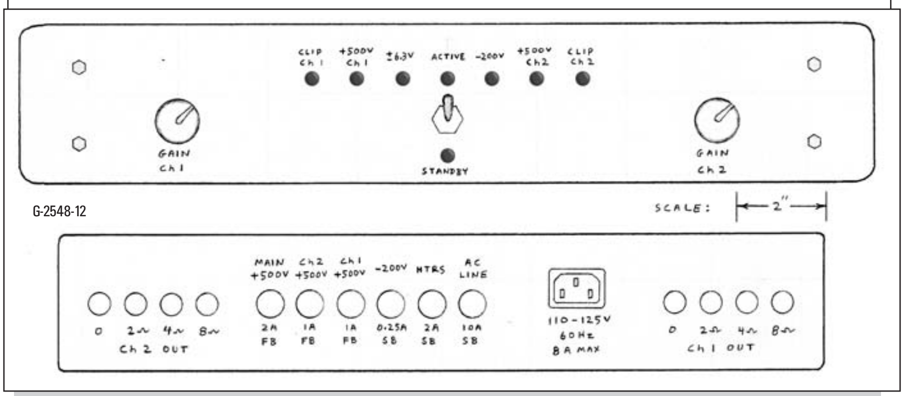
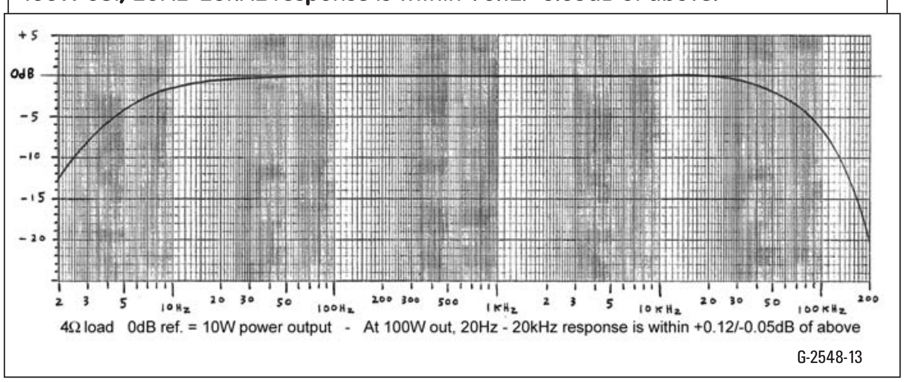


FIGURE 13: Amplifier frequency response. 4Ω load 0dB ref. = 10W power out. At 100W out, 20Hz–20kHz response is within +0.12/-0.05dB of above.



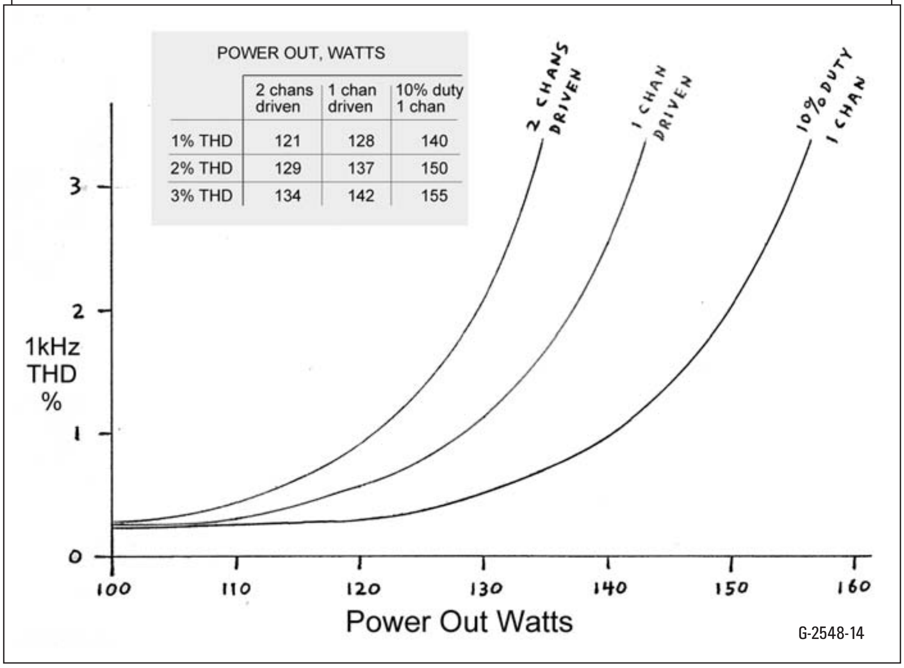
(2.2 sec. time constant); this is the dominant FB loop pole. This also attenuates 20Hz audio signals by 49dB with reference to the DC loop gain. The output of A1 drives the bias diff-amp Q2-Q3, completing the loop.

With matched KT88s, quiescent DC imbalance is held to 0.2mA in the transformer primary. With a 100W 20Hz signal, DC imbalance is less than 1mA. With intentionally mismatched tubes, the corresponding values are 2mA and 3mA.

For an extreme (and unintended) test, when I was (at first) using 33% UL tapping, one KT88 screen resistor blew open during an extended overdriven square-wave test (50mA average, 140mA peak screen current—that KT88 permanently became a beautiful blue "neon" glow lamp after replacing the screen resistor!). But with the open screen resistor (and that tube non-conducting), the servo-balance still held the transformer DC imbalance to 4mA. (Note that with the chosen 67% UL tapping, no amount of overdrive abuse exceeds any KT88 ratings.)

Kevin O'Connor, in his excellent book *Principles of Power*, points out that toroidal push-pull output transformers need much lower DC imbalance current to saturate than conventional E-I transformers. True—I measured 8mA DC imbalance needed to approximately half-saturate the Plitron PAT-4142-00, while the 120W Hammond 1650T needed 50mA. With this servo-balance

FIGURE 14: THD versus power , 1kHz. 4Ω 117V AC line.



circuit, no visible (nor audible) saturation occurs even at 100W, 20Hz with moderately mismatched tubes.

BIAS STATUS LEDS

The "BS+" and "BS–" voltages are averaged by R15-16, LP filtered above 3Hz by C4, and amplified by A2 with variable DC offset from P3. A2 output drives a "LED-comparator" network. First, bias is set to 50mA/KT88 (by measuring 0.50V at "BS+" and "BS–"); then P3 is adjusted so the two LEDs glow equally. From then on, the voltmeter is not needed: a 5mA (per KT88) bias change extinguishes the appropriate ("low bias" or "hi bias") LED, and bias can be adjusted (with P3) to within 1mA by balancing the LEDs' brightness.

The maximum power indicator is very simple. The circuit with P5 set as shown (575Ω, w-ccw) just starts to turn on the red LED at about 100W sine wave power. At clipping onset (about 135W sine) this high-efficiency LED will flash brightly enough to use as a reading lamp.

DAMPING FACTOR CURRENT FEEDBACK LOOP

I've saved the most interesting part of the supplemental functions for last. This uses positive load current feedback (CFB) to cancel part (or all if desired) of the amplifier's output resistance. Don't worry; while this is positive FB, the loop gain is only about –13dB, completely stable. A proven old idea, it's been used in vintage Altec studio amps and (1997) in the Sonic Frontiers Power 2 amp, a 110W per channel stereo tube unit (reviewed in *Stereophile*, May 1997, p. 153).

Transformer primary reflected load current is sensed from the KT88 cathode resistors, summed at the "CS1" and "CS2" points. After some HF comp. (R31-C7) and level control (P4), the differential signal proportional to speaker load current is sensed (with very high common-mode rejection) by T1, a Hammond 560C unit of broadcast quality. As used here, its –1dB bandwidth is about 10Hz–100kHz, with probably less than 0.01% THD. Its output feeds (through R28–29) the 12AX7 cathodes (points "CFB1" and "CFB2"), completing the loop. (Note: Diodes D1 through D6 are not part of the CFB circuit; they

PARTS LIST

Ref.	Description	•	•	Mfr.P/N	Dist.	Dist. P/N
AT1	Step attenuator			DACT CT2 100k-1		
C6,7,10,11	Cap, 5pF, 500V	ceramic disc				
C2	cap, 68pF, 100V	ceramic disc				
C18,19	cap, 1.5nF, 1600V					
C4	cap, 2.4nF, 100V	ceramic disc				
C8, 9	cap, 0.022µF, 1kV		Hovland		AES	C-HD022-1000
C13,14	cap, 0.47µF, 630V	poly	Solen		AES	C-FSD47-630
C1	cap, 2.2µF, 250V	poly	Solen		AES	C-FS2D2-250
C5,12,16	cap, 2.2µF, 630V	poly	Solen		AES	C-FS2D2-630
C17	cap, 6.8µF, 630V	poly	Solen		AES	C-FS6DB-630
C3,15	cap, 47µF, 350V	electrolytic	Panasonic	EEU-EB2V470	DK	P5934
1, 2	diode, Zener 10V			1N5240	DK	1N52408DICT
D3	diode			1N4148		
F1	fuse, 1A FB					
J1	jack, RCA					
J2	Jack, XLR		Neutrik	NC3FP-1-B	Newark	B9F152
L1	inductor, 1.2mH, 1A		Hammond	1540M14		
L2, 3	inductor, 100µH, 100mA		Hammond	1530B104		
P1	trimpot, 2k					
P2	trimpot, 10k					
R43-6	Res, 10Ω, 1%	1W	MF			
R47-50	Res, 100Ω, 1%	¼W	MF			
R55-8	Res, 200Ω, 5%	5W	wire-wound		DK	ALSR5J-200
R59, 60	Res, 300Ω, 5%	5W	wire-wound		DK	ALSR5J-300
R17	Res, 470Ω, 5%	¼W	MF		DK	
R3	Res, 620Ω, 5%	¼W	MF		DK	
R5	Res, 1k, 5%	5W	wire-wound		DK	ALSR5J-1.0k
R8,11,30,15, 37,51–54,39–42	Res, 1k, 1%	1W	MF			
R16	Res, 2.2k, 5%	¼W	MF			
R20	Res, 4.7k, 5%	1W	MF			
R7	Res, 6.8k	¼W	MF			
R12, 13	Res, 5.62k, 1%	¼W	MF			
R2, 4	Res, 10k, 1%	¼W	MF			
R38	Res, 15k, 5%	5W				
R23, 24	Res, 18k, 5%	¼W	MF			
R35, 36	Res, 18k, 5%	2W				
R27	Res, 27k, 5%	2W				
R31, 32	Res, 33k, 5%	2W				
R6	Res, 39.2k, 1%	¼W				
R14	Res, 68k, 5%	2W				
R21,22,33,34	Res, 100k, 1%	1W				
R25,26	Res, 220k, 5%	¼W				
R18,19,28,29	Res, 360k, 1%	2W				
R9, 10	Res, 470k, 5%	¼W				
S1, S2	switch, DPDT (2)					
T1	output transformer				Plitron	PAT-4142-00
V1	Vacuum tube			12AX7	AES	
V2	vacuum tube	12AT7	AES			
V3	vacuum tube			6SN7GTB	AES	
V4-7	vacuum tubes			(JJ) KT88	AES	
A1	op amp			LF411ACN		
A2	op amp			TL081CP		
C7	cap, 3300pF, 100V					
C4	cap, 0.1µF, 50V					
C1	cap, 0.1µF, 630V	∇				
C2, 3	cap, 0.22µF, 50V					
C5, 6	cap, 100µF, 16V	electrolytic				
D1-10	diode			1N4148		
LED5 (6)	LED, violet				Digi-Key	67-1830
LED7 (8)	LED, red				Digi-Key	67-1611
LED9(10) 11(12)	LED, green				Digi-Key	67-1755
P1	pot, 100k Lin	2W Precision		RV4LAYS A 104A	Digi-Key	RV4L104C
P2, 3	trimpot, 100k				Digi-Key	3296Y-104
P4	trimpot, 100Ω					
P5	trimpot, 2k					
Q1-3	transistor, PNP	∇ (Q1)		2SB1011		
R27, 30	Res, 330Ω, 5%	¼W				
R28,29,32,34	Res, 1k, 5%	¼W				
R20, 22	Res, 1.8k, 5%	¼W				
R31, 33	Res, 2.2k, 5%	¼W				
R21, 23	Res, 4.7k, 5%	¼W				
R18	Res, 10k, 5%	¼W				

Continues→

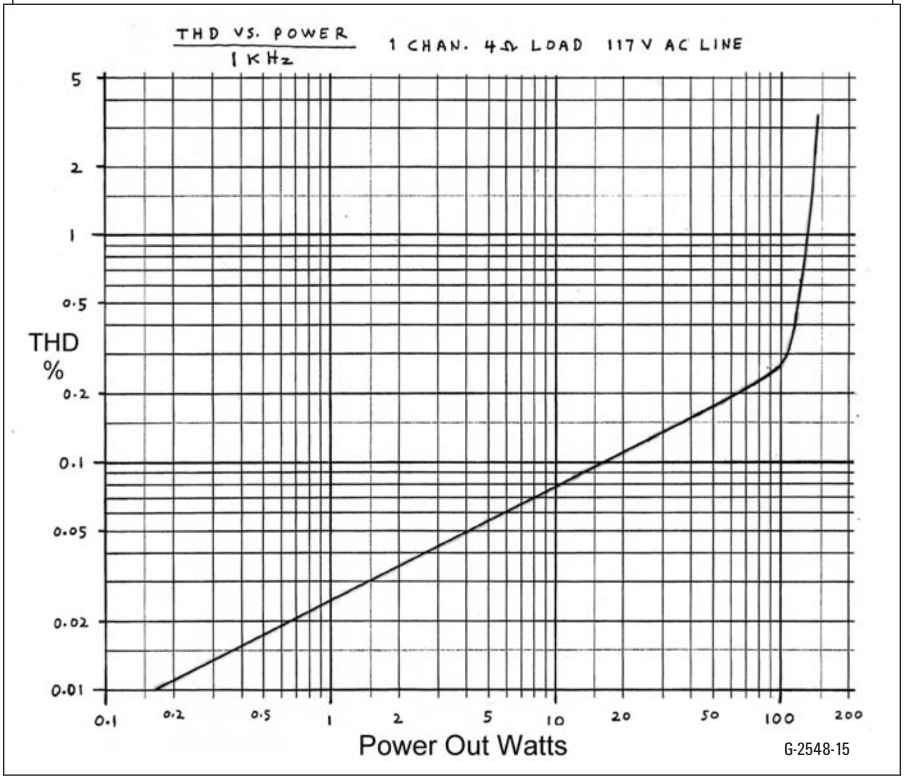
provide current limiting negative FB and are normally out of the picture.)

So for a given amplifier input voltage, lowering the load impedance draws more current, which feeds back more (in-phase) drive voltage to the 12AX7 cathodes. This cancels an adjustable amount of the normal output voltage drop with lower load impedance, effectively "adding" a negative resistance.

Figure 11 shows how positive current feedback (PCFB) generates a negative resistance in series with the positive output R of an amplifier. A unity-gain amplifier with two summed inputs (simplest example) has an output resistance of ra. This drives a load rL, which is ground-returned through a current-sensing resistor rs, of low enough value relative to rL to insignificantly affect the load current io. The analysis shows that the output resistance ro, presented to the load, is ra-rsC. Thus ro can be made positive, zero, or negative.

As adjusted in the Mad Katy amplifier, the plate-to-plate output resistance seen by the transformer primary has the following approximate values: (1) 2kΩ with no FB, (2) 330Ω with the plate-fed 15dB conventional NFB, and (3) –150Ω (yes, negative) with both FB loops. The PCFB loop has "added" a negative 480Ω

FIGURE 15: THD versus power, 1kHz.

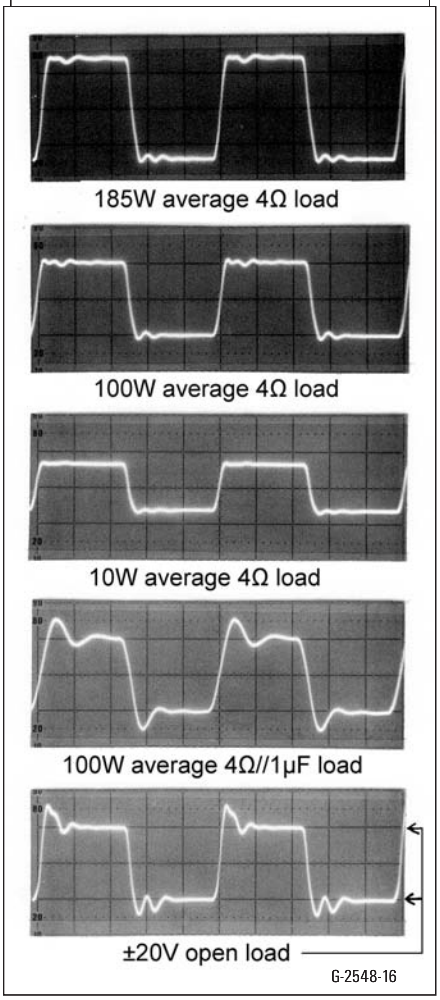


resistance in series with the plate-to-plate output.

While the amp is normally adjusted for a DF of over 20 from 40Hz–10kHz, I had fun cranking up P4 (**Fig. 10**) fully, resulting in an output R of -.8Ω at the 4Ω tap. Mathematically, the DF would be –5, but that does *not* mean "negative damping." On the contrary, at a speaker's bass impedance peak frequency the delivered voltage will actually *decrease*, lowering the "Q" of the bass rolloff. Mathematical "negative damping factor" equals electroacoustic *over*damping.

What was fun was watching a sine wave from the amp output—first with no load, then seeing the voltage *increase* when connecting a 4Ω load resistor! A mechanical analogy would be pushing a heavy wheelbarrow along level ground, then coming to an incline and finding it *easier* to push uphill—you might be "inclined" to instinctively look for a hidden motor!

FIGURE 16: 10kHz squarewave responses.



PARTS LIST CONTINUED

Ref.	Description	•	•	Mfr.P/N	Dist.	Dist. P/N
R26	Res, 15k, 5%	¼W				
R6, 7	Res, 47k, 5%	¼W				
R17	Res, 68k, 5%	¼W				
R13, 14	Res, 100k, 5%	¼W				
R24, 25	Res, 100k, 5%	2W				
R1, 9, 10	Res, 240k, 5%	½W	∇(R1)			
R2	Res, 270k, 5%	¼W	∇			
R19	Res, 330k, 5%	¼W				
R4	Res, 360k, 5%	2W				
R8	Res, 470k, 5%	¼W				
R3	Res, 1M, 5%	½W	∇			
R15, 16	Res, 1M, 5%	¼W				
R5	Res, 1.5M, 5%	¼W				
R11, 12	Res, 10M, 5%	¼W				
T1	Audio Line transformer			Hammond 560C		
BR1	bridge rectifier				Digi-Key	36MB160A
BR2	bridge rectifier				Digi-Key	2KBB100
BR3	bridge rectifier				Digi-Key	KBC102
C6	cap, 10nF, 630V					
C5	cap, 1µF, 6.0V	poly	Solen		AES	C-FS1-630
C8	cap, 2.2µF, 630V	poly	Solen		AES	C-FS2D2-630
C7	cap, 10µF, 630V	poly	Solen		AES	C-FS10-630
C9, 10	cap, 47µF, 450V	electrolytic	Panasonic	EEV-EB2 W470	DK	P5951
C11	cap, 100µF, 350V	electrolytic	Panasonic	EEV-EB2V101	DK	P5938
C12	cap, 560µF, 10V	electrolytic	Panasonic	EEV-FC1A561	DK	P11186
C15, 16	cap, 1000µF, 15V	electrolytic	Panasonic	EEV-FC1C102	DK	P10253
C1-4	cap, 1500µF, 350V	electrolytic		ECE-T2VA152FA	DK	P10671
C13, 14	cap, 4700µF, 25V	electrolytic		EEV-FC1E472	DK	P10289
CL1-3	cap, 4700µF, 25V	electrolytic		CL70	Digi-Key	KC007L
D1, 2, 3, 11	diode, zener 10V			1N5240	Digi-Key	1N5240BDICT
D4-10, 12-14	diode, zener 68V			1N4760	Digi-Key	1N4760ADICT
D15	diode			1N4148		
F1	fuse, 10A SB				DK	F483
F2	fuse, 2A FB				DK	F119
F3	fuse, 0.25A SB				DK	F310
F4	fuse, 2A SB				Digi-Key	F325
LED1	LED, green				Digi-Key	67-1755
LED2	LED, red				Digi-Key	67-1611
LED3, 4	LED, blue				Digi-Key	67-1750
MOV1	transient absorber				Digi-Key	ERZ-V200201
PE1	Power entry module	PREO 10ERM1			Digi-Key	364-1042
Q1-3	power MOSFET	N channel	IRC	IRFBE30	Digi-Key	
Q4	power MOSFET	P channel	IRC	IRFR 9310	Digi-Key	
Q5	transistor	PNP	Panasonic	2SB1011	Digi-Key	
R41	Res, 0.33Ω	35W	Ohmite		Digi-Key	TCH35PR330N
R24	Res, 100Ω, 5%	2W BC			Digi-Key	BC100W-2CT
R37, 38	Res, 121Ω, 1%	¼W				
R13, 25	Res, 470Ω, 5%	2W BC				BC470W-2CT
R35, 36	Res, 487Ω, 1%	¼W				
R42, 43	Res, 1k, 5%	¼W				
R9, 10	Res, 2.7k, 5%	¼W				
R30	Res, 5.6k, 5%	¼W				
R31, 34	Res, 6.8k, 5%	¼W				
R32	Res, 10k, 5%	¼W				
R40	Res, 18k, 5%	¼W				
R19, 39	Res, 22k, 5%	¼W				
R33	Res, 27k, 5%	¼W				
R5	Res, 27k, 5%	1W				
R29	Res, 33k, 5%	2W BC			DK	BC33KW-2CT
R17, 27, 28	Res, 47k, 5%	2W BC			DK	BC47KW-2CT
R7, 11, 15	Res, 47k, 5%	¼W			DK	
R26	Res, 56k, 5%	2W BC			DK	BC56K-2CT
R1-4	Res, 68k, 5%	2W BC			DK	BC68K-2CT
R16, 22	Res, 100k, 5%	1W BC			DK	BC100KW-1CT
R14	Res, 100k, 5%	2W BC			DK	BC100KW-2CT
R21	Res, 180k, 5%	1W BC			DK	BC180KW-1CT
R12, 18	Res, 220k, 5%	2W BC			DK	BC220KW-2CT
R6, 8	Res, 470k, 5%	2W BC			DK	BC470KW-2CT
R20, 23	Res, 1M, 5%	1W			DK	BC1.0MW-1CT
S1	switch, DPST	20A NKK		S331	DK	360-1191W
S2	switch, SPDT	NKK		M2022S2A1W01	DK	360-1156
T1	transformer, 9V, 9A			Hammond 182N9		
T2	transformer, 350V, 1.8A			Plitron 097053201		
T3	transformer, 220V, 0.07A			Plitron 007029201		

This method of DF increase, if properly implemented, does not compromise stability or transient response, as opposed to using a large amount of conventional negative voltage FB. Also, because the current FB is already positive (with much less than unity loop gain), phase shifts can only steer the loop phase toward negative, which will only further increase the stability margin. Phase shifts, such as from LF and HF rolloffs, will reduce the DF increase. As set, the DF drops to 13 at 20Hz and 9 at 20kHz.

If you desire a relatively low DF, P4 can be set fully counterclockwise, shutting off the CFB loop. DF is then about 4.

P4 has a DF range (midband, where unassisted DF is highest) of approximately 4, through infinity (zero output R) to about –5. DF numbers are the inverse of a physical parameter (resistance), so the "infinity" spike is only a contrived mathematical singularity; as P4 is advanced, the amplifier's R_{OUT} smoothly decreases from (approximately 4Ω tap as an example) 1Ω, through zero, to –0.8Ω.

The only warning is that when set for a negative output R, the amp won't be short-circuit stable. With maximum P4 setting, the output R is about –0.2 × the transformer output tap value; the magnitude of this is the lower load limit for stability, e.g., about 0.8Ω at the 4Ω tap.

Figure 12 shows the front and rear panels. **Figures 13–16** show some graphic performance data.

Next month we'll take a look at this unit's power supply and then begin construction. *aX*

REFERENCES

1. "Norman Crowhurst's Twin Coupled Amp—and Beyond" by John Stewart, *aX* 8/04.
2. "Designing Your Own Amplifier" by Norman Crowhurst, 6/00 *GA*, Fig. 1.
3. "Considering Negative Feedback—" by Dennis Colin, *aX* 12/03.
4. "Odds and Evens" by Graham Dicker, *aX* 7/01.
5. "The Future of Vacuum Tubes in Audio, Part 2" by Lynn Olson, 4/00 *GA*.
6. Joseph Norwood Still (response to letter by Jim Windgassen), 2/00 *GA*, p. 62.

PARTS LIST CONTINUED

Ref.	Description	•	•	Mfr.P/N	Dist.	Dist. P/N
T4	transformer, 9V, 1.67A			Hammond 182H9		
T5	transformer, 15V, 8A			Hammond 182N15		
VR1	reg, pos, adj			LM317T		
VR2	reg, neg, adj			LM337T		

Misc. (for both channels)

Description	•	•	Mfr.P/N	Dist.	Dist. P/N
Socket, octal (10)				AES	P-ST8-209M
Socket, 9 pin (4)				AES	P-ST9-211M
Fan, 12V DC 124mA	120 × 25mm	Papst	3412L	DK	381-1080
socket, octal (10)	1⁄16″ hole 1½″ centers			AES	P-ST8-CIR-8
socket, 9 pin min. (4)	⅞″ hole 1 ⅛″ centers			AES	P-ST9-511
fuse holder (6)	3AG	Littelfuse	342014	DK	F006
wire, green, 300V (100´)	18AWG	Alpha	3055GR005	DK	A2064G-100
wire, red, 600V (100´)	24AWG	Alpha	3070RD005	DK	A3070R-100
wire, blue, 600V (100´)	24AWG	Alpha	3070BL005	DK	A3070L-100
wire, violet, 600V (100´)	24AWG	Alpha	3070VI005	DK	A3070V-100
knob (2)	0.75″∅	Kilo			226-4011
Sil-Pad K10 (20)		Berquist	K10-54	DK	BER114
Grommet (one 100 pkg)	for ⅜″ hole	SPC		NWK	32F1353
Grommet (one 100 pkg)		SPC		NWK	31F2282
Handle (2)	4.562″ centers	10-32 screws	HH smith	NWK	94F8976
Lug terminal strip (25)	2.625″ centers	cinch	56A	NWK	29F591
wire, Teflon, 1000V, red (100´)	22AWGF	Alpha	5875 Red (3)	NWK	
rubber bumper (one 49 pkg)	0.70″∅ 0.38″	H SPC		NWK	92N4782
wire, yellow, 300V (100´)	22AWG	Alpha	3051YL005	DK	A2016Y-100
wire, orange, 300V (100´)	22AWG	Alpha	3051OR005	DK	A2016A-100
AC line cord	9´ 10″	Qualtek	312040-01	DK	Q120
knob (2)	0.925″ ∅	Kilo			226-4012