Current Drive for Headphones -- The Super Linear Transconductance Amplifier
XEN Audio
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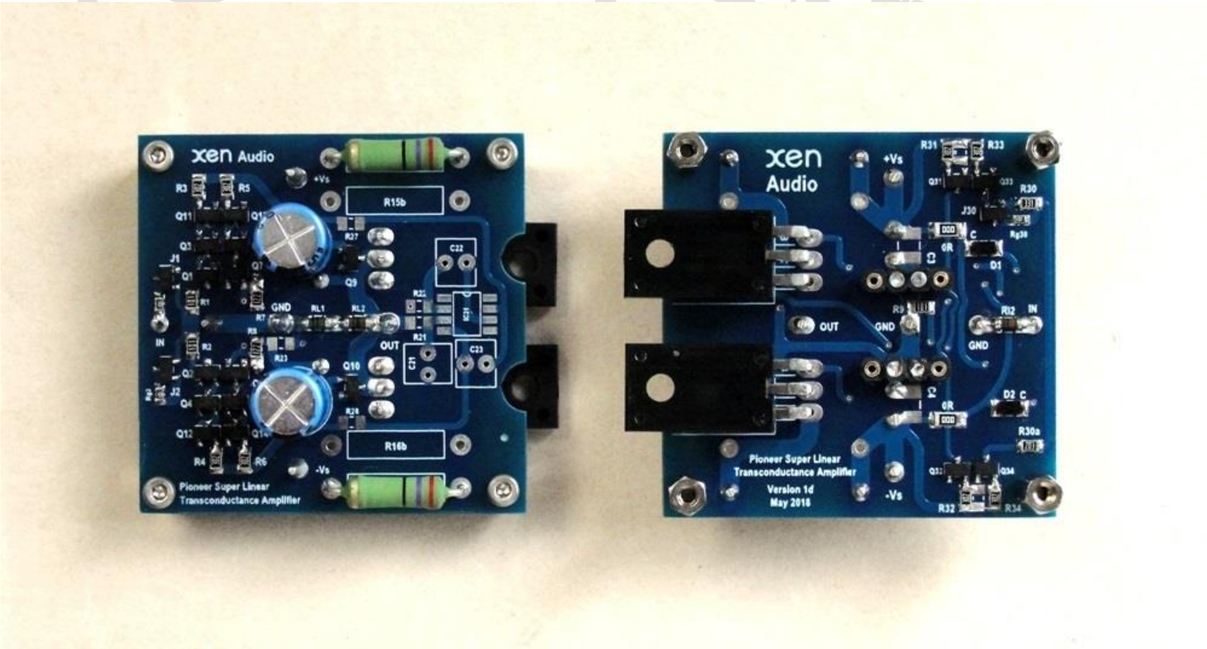


Background

In recent years, there have been a few products on the headphone amplifier market that promotes current drive [1,2]. Current drive is of course no new ideas, especially for loudspeakers. Many articles and books have been published on the topic in the last decades [3,4,5,6,7]. One of the current drive amplifiers well known to DIYers is perhaps the First Watt F1 by Nelson Pass. While there are claims for advantages in transient behaviour and lower distortion in loudspeakers, these appear not to be equally applicable to headphones [6,8]. In fact, the typically variation in impedance of most conventional headphones over the audio band will be reflected in significant difference in the frequency response compared to the same driven in voltage mode.

In his website on current drive [8], Esa Meriläinen discussed how much benefit can be had from using current-drive on headphones. “In electrodynamic headphones, the achieved benefits of current drive are usually very minor compared with the improvement in loudspeaker operation. This is mainly because in the impedance of headphone transducers the relative proportion of the DC resistance is generally much higher than in speaker drivers, so the interfering current components produced by the electromotive forces are left rather small even on voltage drive. …… As with loudspeakers, the frequency response of headphones also exhibits certain changes when moving to current-drive. These changes may, depending on the case, also result in undesirable impressions.”

The one exception is of course modern planar magnetic headphones, which have a characteristically constant impedance over the entire audio band. In a review of a commercial product which offers selectable current and voltage modes, claims of the above-mentioned advantages of current drive have been reported when tested with planar magnetic headphones [9].

Super Linear Transconductance -- Circuit Description

A current drive amplifier is nothing more than a very linear transconductance amplifier. That is, one that converts a voltage input into a linearly proportional current output, irrespective of load impedance. This, as in voltage amplifier design, can be achieved with or without negative loop feedback.

Apart from the First Watt F1, another transconductance design well known to the DIYers is the Rasmussen Transconductance Amplifier [10]. The latter uses a standard chip-amp IC with the feedback taken from a ground-connected current-sensing resistor in series with the load. This is probably the easiest way to do current drive if any stability issues can be dealt with. And there are a variety of power opamps capable of driving headphone loads, not the least the LM1875, for example. Note that in such designs, the negative output is not grounded so it requires 4-wire connection to the headphone, as in a balanced headphone amplifier.

There are also a few efforts by DIYers specifically designed for headphones [11,12,13]. As shown by the two examples from Japan, a most convenient way to make a transconductance amplifier is by means of current mirrors. We have done a few voltage amplifiers for headphones in the past based on current conveying with zero global feedback (ZGF). Some of them also make use of current mirrors, e.g. the UTHAiM and the Pioneer Super Linear (SL) [14,15].

Therefore, all we need to do is to change the current mirror from 1:1 current ratio in the said circuits into something like 1:150, to ensure we have sufficient bias at the output stage. This is because, for example, the input stage of the SL circuit is biased at 1mA, and we wish to have 150mA bias current for the output. On top of that, we need to make sure that the current mirror still retains excellent linearity, as the lack of it converts into distortion in the output current.

Both the UTHAiM and the Super Linear can be converted to current drive, as they already have the necessary current mirrors in place. In fact, any transconductance frontend such as the Marantz HDAM-SA3 [16] can be used. But the Pioneer Super Linear has been proven to be very linear, so we shall use it here as an example. BJTs are also used exclusively in the current mirrors. To start with, it is much easier to make current mirrors with large current ratios using BJTs, as the PN junction of a small signal BJT does not differ to that of a power BJT anywhere as much as in the case of FETs. However, to make sure that the base current of the output stage does not load the input stage of the current mirror excessively, the hfe of the output device has to be at least 100x larger than the current ratio in the mirror. This again points to Darlington's. One known design [17] uses medium-power BJTs in the current mirror cascoded by power devices to take the dissipation, which of course is clever. But these medium-power BJTs just does not have high enough hfe (~100), even though in that particular design, the current ratio was only about 10x.

When using Darlington's for the output stage, we have to add one additional diode drop for the input current mirrors. We can simply add a diode in series with each emitter resistor there, but then we can much better make use of the opportunity to use a full 4-transistor Wilson mirror.

Another deciding factor is value of the emitter resistors. In this particular case, with the use of a power Darlington at the output of the current mirror, a high voltage drop across the emitter resistors will reduce distortion. At some stage, there will be diminishing return, and thermal distortion starts to kick in. Simulations showed that 3V seems to be a good compromise. But 4W low-tempco emitter resistors would be required for the output stage to avoid excessive thermal distortion.

The next decision is how much transconductance. In the original SL, we set the voltage gain at 10x, so as to allow for 3x attenuation of the passive Danyuk cross-feed filter. If we maintain an equivalent 10x voltage gain for a 30R load, we shall end up with 33x for 100R load, and 100x for 300R. This is obviously too high. So assuming we want to cater for loads between 30R and 300R, it is a good compromise to set the transconductance for 100R. For a 10V output at 100R load with 1V input, the transconductance should be 100mS. And since the current ratio of the current mirror is already set at 150, the input degeneration resistor should be 1.5k. That is to say, the equivalent resistance of R7, R8, R9 should be 1.5k. If your headphones are somewhere between 60R and 600R instead, you can further increase these by a factor of 2.

As in the voltage-gain SL, one needs to trim the upper and lower output stage bias for zero DC offset. In order to avoid any plug-in thumbs, it is wise to connect the output to Gnd with a 2k dummy load. This will hardly have any effect on the output once the load is plugged in. But it provides a Gnd reference to the output, as well as makes life easier for DC trimming.

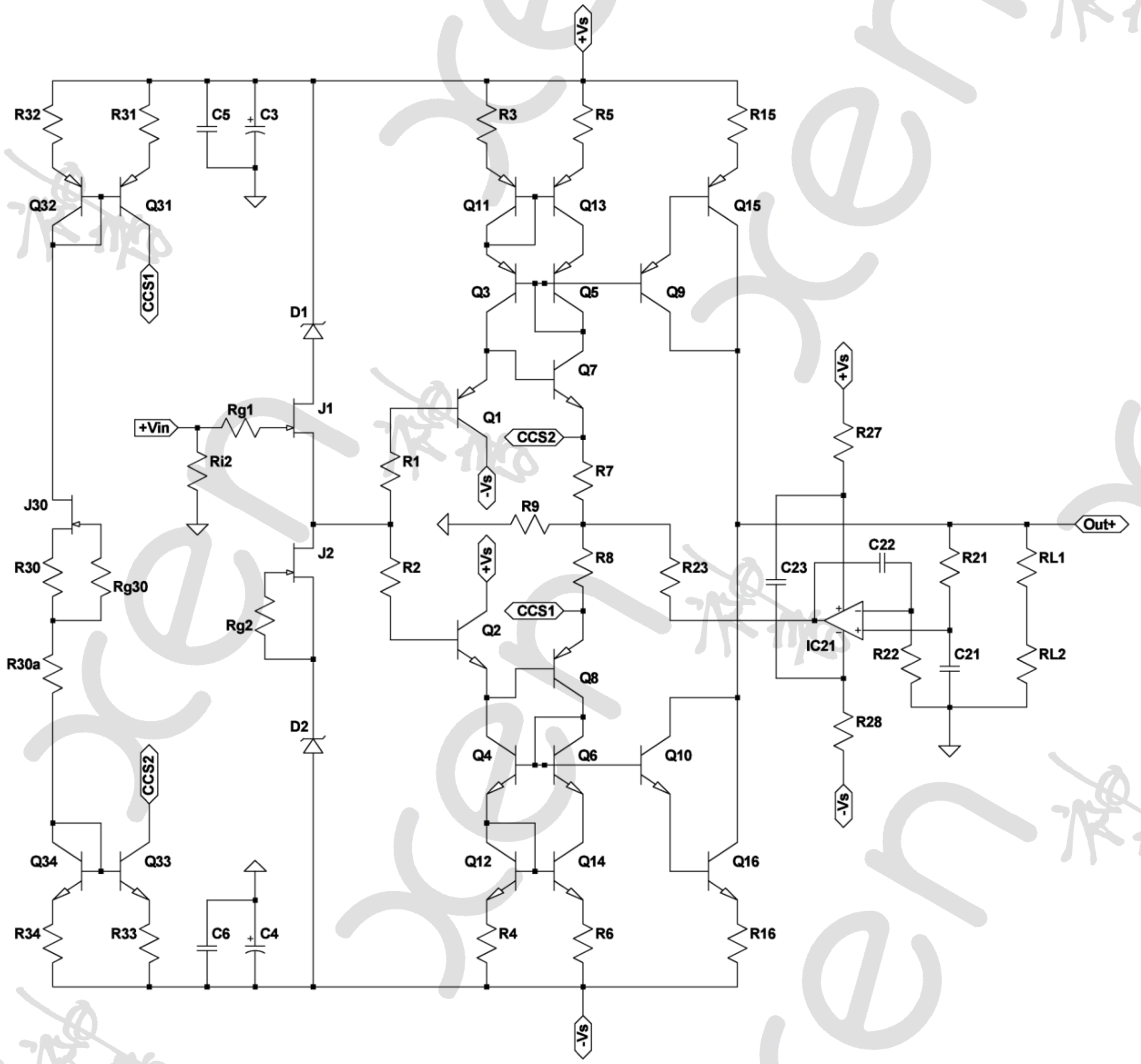
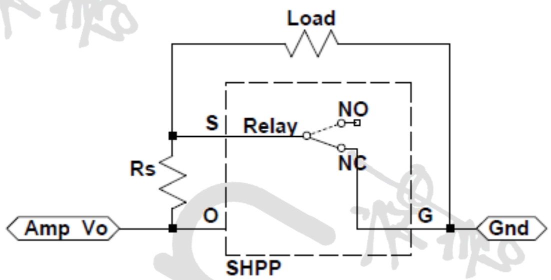


Fig. 1 Pioneer Super Linear Transconductance Headphone Amplifier Schematics

One big advantage of current drive is non-invasive protection. In case of excess DC current, one can simply shunt the output to Gnd without having to disconnect the load. The output socket can therefore be wired to the amplifier permanently without any relay contacts in between. The protection circuit is not in the signal path and is thus non-invasive.

An example of the protection circuit was posted in Ref.12. This, however, still made use of output voltage sensing. If the headphone is not connected to load, the offset voltage due to a minute DC current would become huge. So this is perhaps not the best solution.

Luckily, the standard XEN SHPP [18] already provides a differential sensing. This can therefore be utilised to detect any DC current flowing through the amplifier output via a small current sensing resistor Rs (e.g. 10R). This sensing resistor has no significant influence on the performance, as it is small relative to both load resistance and output impedance. Since the circuit was set to work at 30R to 300R load, a DC threshold current of 1mA seems appropriate. This corresponds to 0.3mW dissipation at 300R, and 0.03mW at 30R. At 1mA DC current, Rs will generate a DC voltage of 10mV. So the SHPP gain has to be increased to 68, by simply changing the values of R2, R4 to 680k. Point S should now be connected to output to headphone, just after Rs. Point O should be connected to the amplifier output before Rs. The Normally Closed contact of the relay will short the headphone output to Gnd during start up or in case of fault. This is released during normal operation. All 3 connection wires can be tapped conveniently at the output socket, where the sensing resistor Rs should also be placed. Rs needs to be at least 2W due to worst-case dissipation by AC signals.



The beauty of this current sensing solution is that the DC current detection is still active, even when the output is shunted to Gnd. This will not be the case for a voltage-based solution.

The SHPP relay is rated at 2A, so it is also useful to have a current limit in the power supply, which is the case for our simple discrete regulator used in the SL.

DC Servo Options

Previous experience with the CCS biased Pioneer Super Linear Headphone Amplifier has demonstrated that output DC offset is stable over time. Hence, once adjusted, a DC servo is not necessary. Nevertheless, just for the sake of circuitry exercise, it is useful to consider a few options.

The most obvious solution is to use a similar configuration to the SL voltage amp. However, since the output Riv network no longer exists here, the servo would have to be connected to the input side. Now consider that the servo opamp has an output noise of *v*. This will be reduced by a factor of 10 by R23, before it appears at R9, where it is converted to a noise current of (0.2.*v* / R7). The output current mirror multiplies this by a factor of 150, before it is converted to a noise voltage at RL. Using the default values and a load of 100R, the noise at load is ~ *v*.

Suppose we try to tap the current out of both the top and bottom output current mirrors [17]. The opamp noise voltage will appear as a noise current given by 2.*v* / (R41+R15). This in turn appears as a noise voltage at load. Using R41 = 1k and a load of 100R, the output noise voltage is 0.2*v*. So this appear as a clear advantage.

However, since the servo is now connected indirectly to the top and bottom rails, power supply noise, when not 100% equal and opposite, will appear also at the output. Suppose the top rail alone has a noise voltage of v_s. The resulting noise voltage at load is given by $2.v_s.RL / (R42+R15)$ and is thus about $0.2.v_s$, using the same values as above. In other words, we have a PSRR of -15dB, which is of course not brilliant. As the rails are usually a lot noisier than the opamp output, this can be a worse solution than the first one.

Unless of course we can configure the DC servo to drain a DC current directly at the load. But since the DC offset voltage is going to be a minute amount compared to the AC signal, this cannot be a simple voltage output and a large series resistor. Rather, it has to be something like a Howland current source instead. And that is getting a little bit complicated.

The final verdict goes back to the first one.

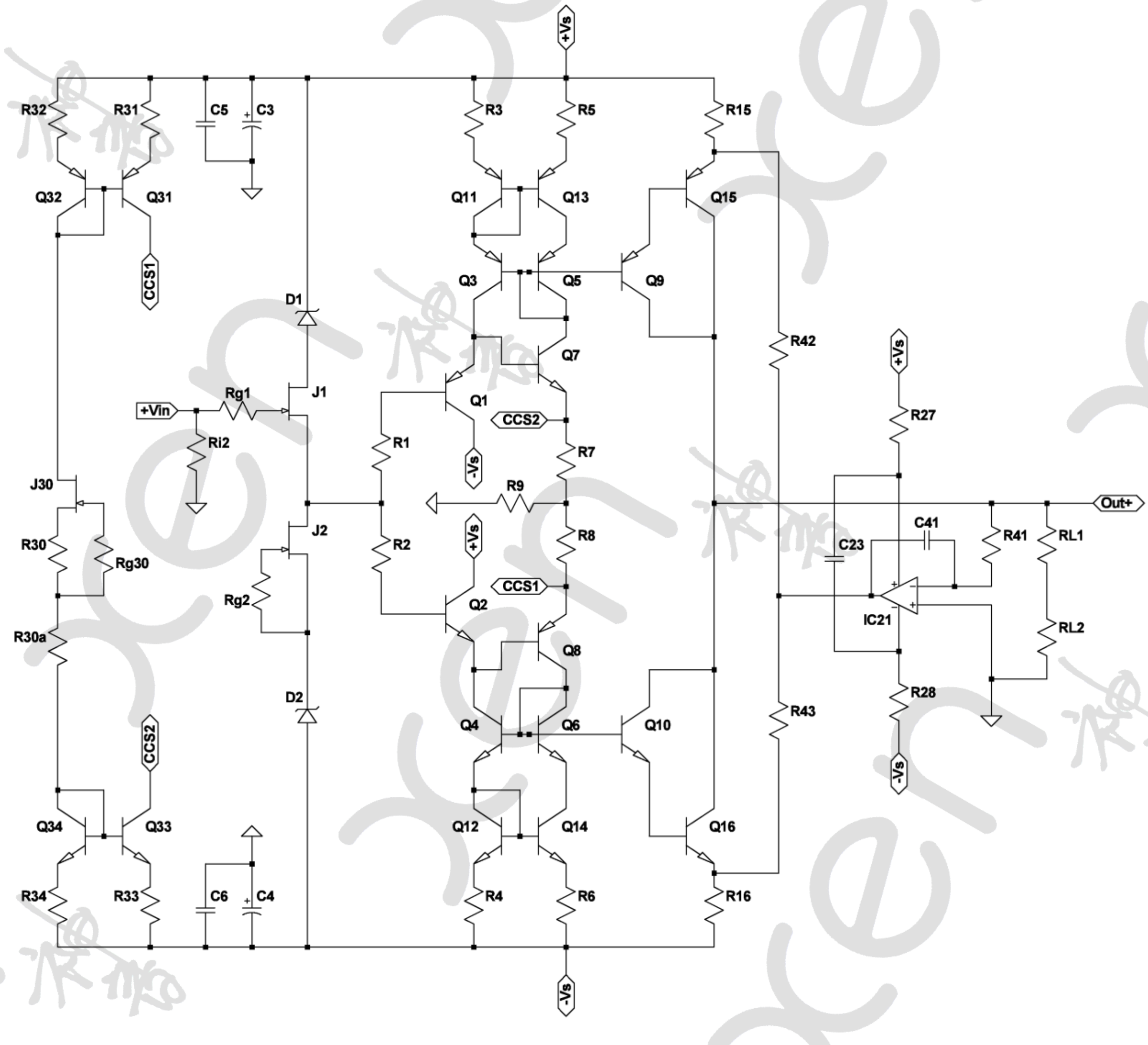


Fig. 1a Pioneer Super Linear Transconductance Headphone Amplifier – Alternative DC Servo

Zobel Network for Headphones

For many modern planar magnetic headphones, their impedance is almost constant over the audio band. As such, there will be little difference in the frequency response between voltage and current drive. However, for many other voice-coil headphones, they typically have a large resonance peak at 100Hz or below, and then a slower rise in impedance at HF, due to coil inductance. Typical examples include the Focal Elear and the Sennheiser HD800S.

While a few dB extra SPL might not be too much harm, the resonance below 100Hz do need some linearising. Especially in the Focal Clear, the peak impedance at 50Hz is 4x that of the nominal impedance. Just as in loudspeaker design, a RLC shunt network can be added to notch down this impedance peak, if so wished. An example for the Focal Elear is shown below, after having established an equivalent circuit for the headphone coil. But one has to ask the question in such cases why current drive at all.

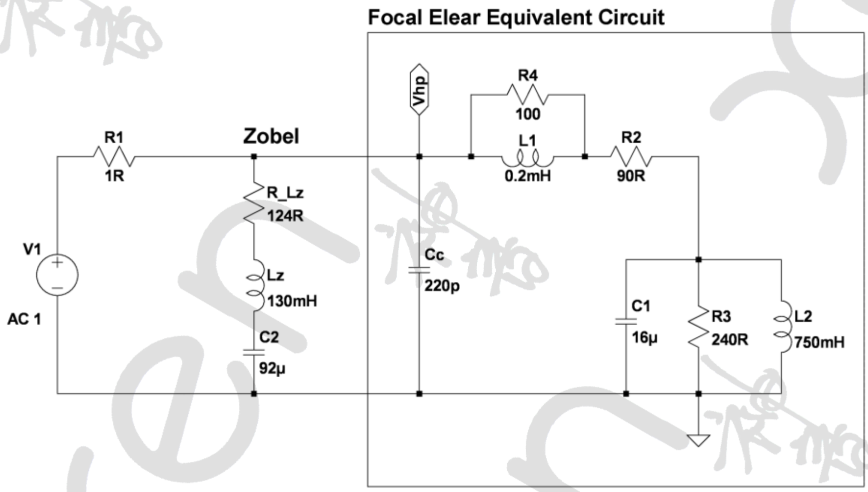


Fig. 2 Zobel Network for Focal Elear

Dual Current & Voltage Modes

Just as any transconductance amplifier, e.g. the Borbely EB602/200, a voltage negative feedback loop can be used to convert this to a voltage amplifier. A low-distortion, ZGF transconductance amplifier would of course be a good basis. The result of voltage NFB is lower output impedance, which will solve the issue with headphones of large impedance variation. The open-loop transconductance can also be tailored to give the desired amount of NFB (and hence output impedance), even to allow it to work in a sort of mixed voltage / current mode. Of course, this somewhat destroys the purpose of current drive in the first place, but it does give one the flexibility of both modes to suit different headphones.

An example has been included here. The voltage feedback part can be grouped together in a stack-on daughter board. Removing that reverts the amplifier to pure transconductance mode with zero global feedback. Using the components in Appendix 2, the simulated output impedance is approximately 9R in voltage mode, and 16k in current mode, for loads between 30 and 300R. They can thus be considered as purely voltage / current amplifiers respectively.

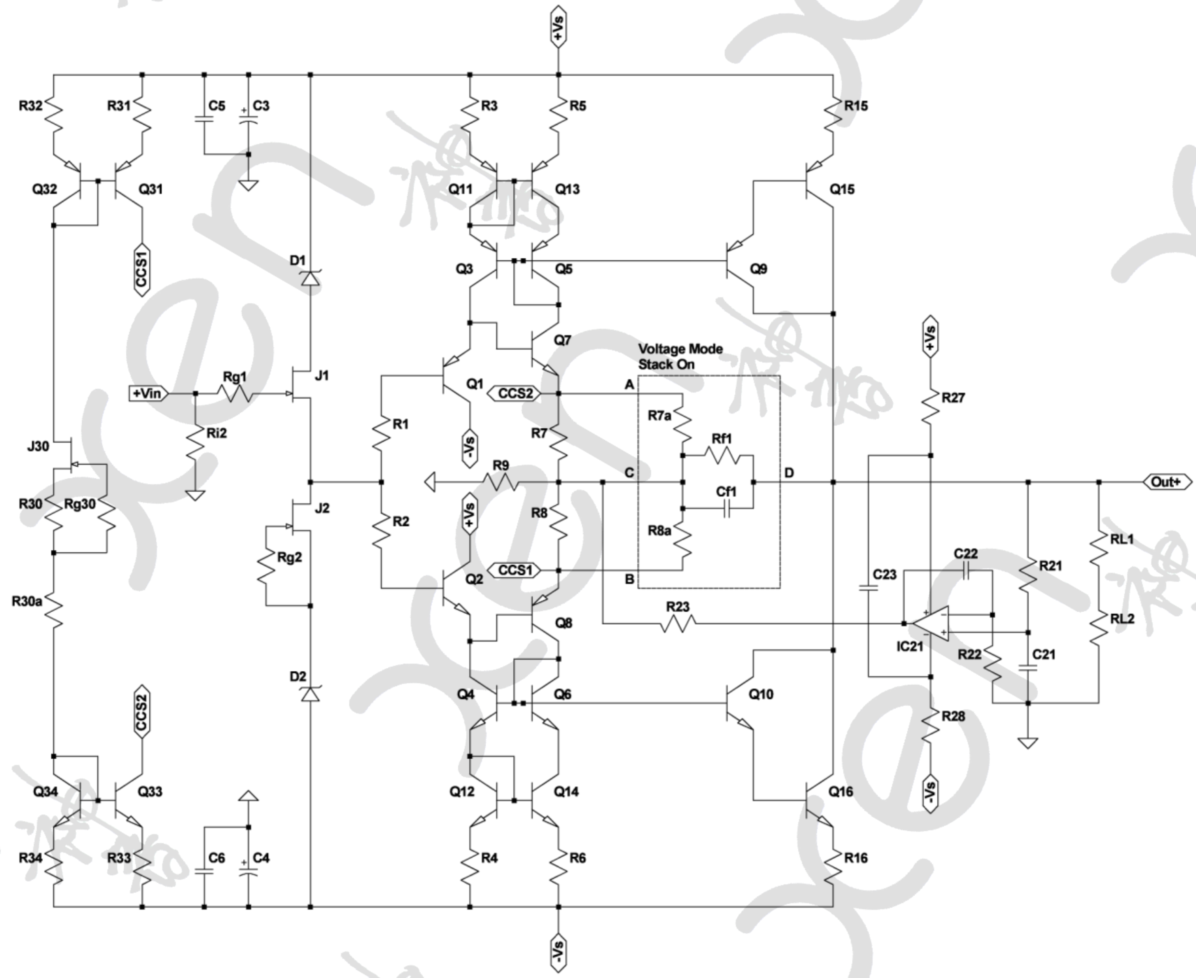
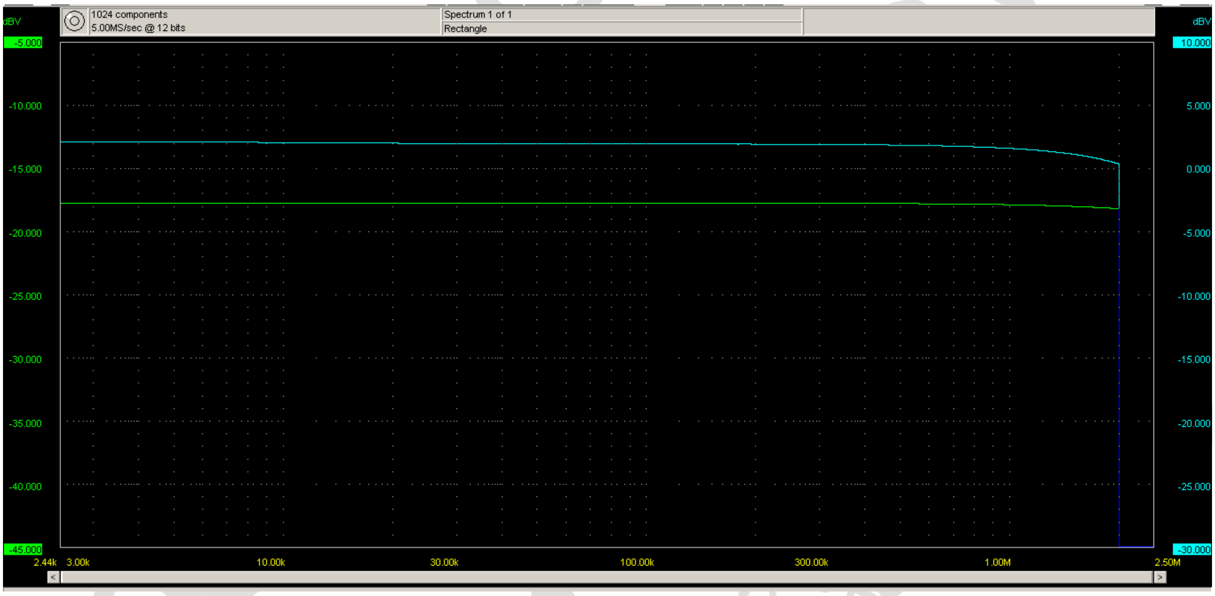


Fig. 3   Pioneer Super Linear Transconductance Headphone Amplifier with Voltage Feedback

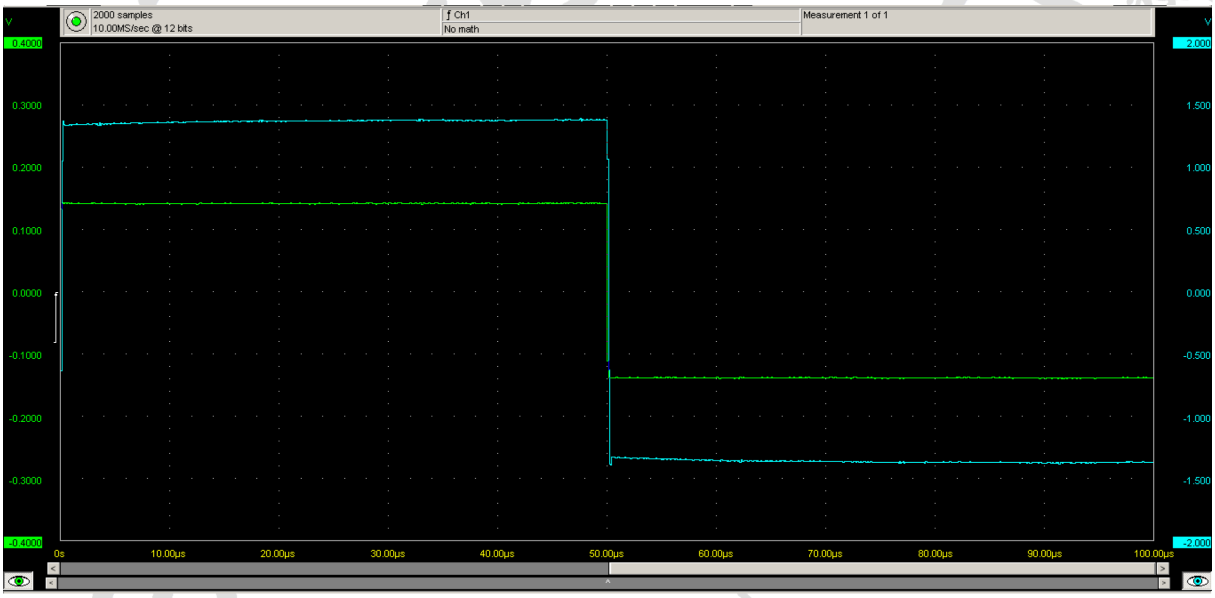
Measurements

A pair of prototypes were built which were optimised for 50R load (by changing R7,8 to 1.2k), and they both worked first time, meeting expectations from simulations. DC offsets were 70mV on both channels on 50R load, and were trimmed by paralleling a 330k resistor with R31. Once trimmed, it was stable over time to <2mV. 50R load was chosen for testing as this corresponds to many planar magnetic headphones on the market. Gain at 1kHz was exactly 10.40 on both channels.

Bandwidth in current mode is -1.5dB at 2MHz. Square wave response has no overshoot. The voltage mode was also tested with no load. No oscillation was observed, and bandwidth was even higher at -1dB at 2MHz.



Current Mode Frequency Response



10kHz Square Wave Response

Bias was 160mA as expected. If you do wish to fine adjust bias, you can change the current in J30 by varying the value of R30. This allows the bias to be changed without affecting the current gain. You can of course also adjust bias by changing R15, 16. But this will change the current gain at the same time.

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Appendix 1 Bill of Materials

Per Channel (max. +/-24V rails)

Quantity	Designation	Description	Alternative
7	Q1,3,5,8,9,11,13	2SA1312BL, matched hfe	BC807-40
7	Q2,4,6,7,10,12,14	2SC3324BL, matched hfe to the above	BC817-40
1	Q15	2SA1859	D45H11
1	Q16	2SC4883, matched hfe to Q15	D44H11
2	Q31,33	2SA1312BL, matched hfe	BC807-40
2	Q32,34	2SC3324BL, matched hfe to the above	BC817-40
1	IC21	OPA604, SOIC	optional servo
2	J1,2	2SK209GR, matched Idss ~4mA	
1	J30	2SK209GR	
2	D1,2	BZT52 12V SOD123	
2	R1,2	Susumu 0805 100R 0.5%	
1	Ri2	Beyschlag MMA 0204 100k 1%	
4	R3~6	Susumu 0805 3k 0.1%	
2	R7,8	Susumu 0805 2.8k 0.1%	
1	R9	Susumu 0805 100R 0.1%	use 110R with servo
4	R15,16	2x // Welwyn ULW2 39R 5%	match to <1%
2	R21,22	Susumu 0805 1M 1%	optional servo
1	R23	Susumu 0805 1k 0.5%	optional servo
2	R27,28	Susumu 0805 22R 0.5%	optional servo
1	R30	Susumu 0805, trim J30 to 1mA	
1	R30a	Susumu 0805 20k 0.5%	
4	R31~34	Susumu 0805 3k 0.5%	
3	Rg1,2,30	Susumu 0603 220R 0.5%	
2	RL1,2	Beyschlag MMA 0204 1k 1%	
2	C3,4	Rubycon ST 1206 0.47µ 35V	optional
2	C5,6	Nichicon KA 220µ 35V	
3	C21~23	WIMA MKS02 1µ 63V	optional servo

Optional DC Servo

When not using DC servo, omit IC21, R21 ~ 23, C21 ~ 23. Change R9 to 100R.

Appendix 2 **Bill of Materials for Dual Voltage / Current Mode**
Per Channel (max. +/-24V rails)

A) Current Mode (same as Appendix 1)

b) Voltage Mode Stack On **(Gain of 10)**

2	R7a,8a	Beyschlag MMA 0204 100R 0.1%
2	Rf1	Beyschlag MMA 0204 1k 0.1%
2	Cf1	SMD Mica 22p 1210