SIMPLE, ACCU RATE RIAA EQ PHONO AMPLIFIER

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A simple and cost effective high-performance phono amp that will deliver all you need sonically to be able to enjoy your LP's. You may find slightly quieter phono amps and you may find some that are a just little more accurate or have a few more features. However, this all-active design offers the best bang for your buck by far. Utilizing the industry proven NE5534A op-amp, it features a 76 dB signal to noise ratio and a 26dB overload margin (ref 5mV input and Low gain) and can be built for about £25 ($35). It uses a single sided PCB which of course makes it ideal for DIY enthusiasts who want to etch their own boards. No SMD components are used, further easing assembly and construction. You will require a regulated power supply of ±12 to ± 18V (±15 recommended) to run this EQ amp – a circuit and PCB layout for this is also provided. A BOM for both is included for parts that can be sourced from Mouser.

Photo above: Technics Turntable by David Gallard / Flickr (CC)

Introduction

LP records are back in fashion. Who would have guessed 15 years ago that an 80-year-old technology would make such an incredible comeback? Apparently, vinyl is cool whilst CD's and digital are not. Now, digital downloads still outweigh vinyl by a huge margin, so do not expect that to change anytime soon. However, some fantastic music is being released on vinyl. And isn't it great to give those LP's you bought in your misspent youth a spin on a decent, modern turntable? Hi-Fi magazines are awash with turntable and cartridge reviews; complete systems with an integrated MM phono EQ amp start for as little as £150 ($200) all the way up to units retailing at a staggering $650 000 – and that's before you've added a cartridge and a phono amplifier – and it is quite easy to spend another £50 000 on these as well. It seems the sky is the limit when it comes to vinyl. What does it take to get you to say 90% of the full potential performance of an LP? Keep in mind that a *good* LP has a signal to noise ratio of 50dB and a dynamic range of not more than 65 dB. You would be very lucky indeed to have something considerably better than this. Actually, not much it turns out!

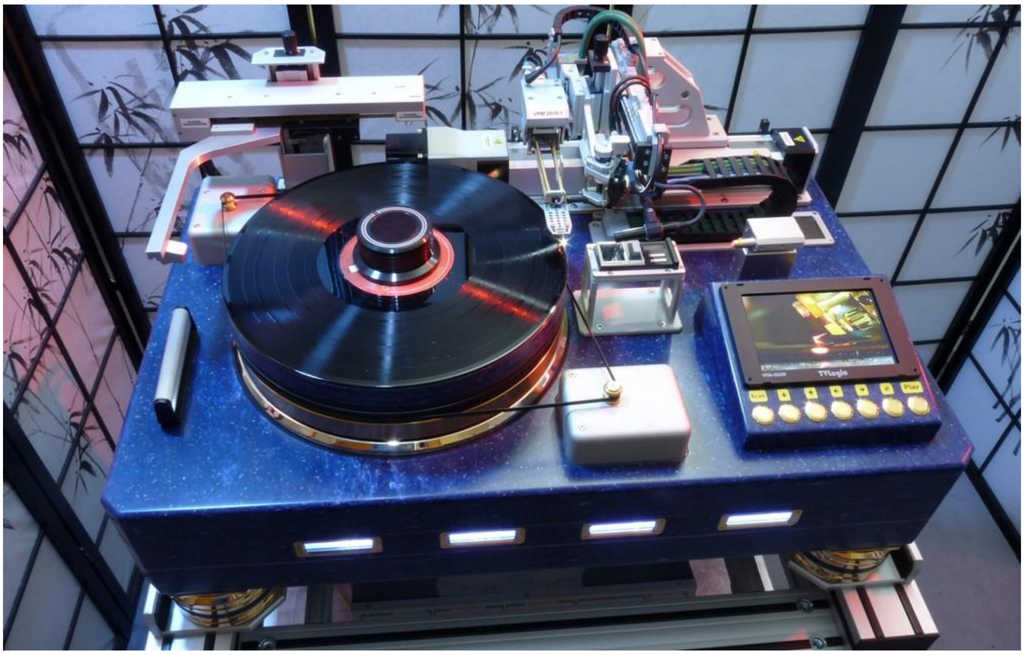


FIGURE 1 - THE AV DESIGN HAUS' DERENEVILLE VPM 2010-1 RETAILING AT $650 000

Some History

All of the major engineering challenges of pressing and then extracting the sound encoded on an LP's grooves were solved in the early 1960's when the RIAA specification was adopted industry wide. Prior to this the numerous EQ standards caused some consternation for consumers. Turntables and pick-up arms for the most part though were acceptable but not great and really only came of age in the 1970's, epitomized by the Linn Sondek LP12, still held in awe by audiophiles. In 2018, good second-hand exemplars will regularly fetch over a £1000 on ebay, 40 years after they first appeared[1]. Advances in CAD/CAM, tighter manufacturing tolerance capabilities and newer, more readily available materials (e.g. carbon-fibre, Teflon, modern acrylics, and plastics) mean that contemporary turntables are streets ahead of their older counterparts. The original Project Debut turntable that first retailed for £120 here in the UK in the late 1990's, was a good example of the kind of performance one could get for the money from a modern design.

[1] A limited series of 40 units were issued by Linn to mark the LP12's 40th anniversary in 2012 with plinths made from Highland cask oak, retailing at $25 000 each . . .

Towards an Intuitive Understanding of RIAA EQ

The cutting head used to engrave the acetate master for an LP (from which the pressings are eventually derived) is a velocity transducer. This means that *if you cut the groove at constant amplitude vs frequency*, the output from your MM phono cartridge on your pick-up arm - which also a velocity transducer – will rise at 20 dB/decade. So, if we want a flat audio response out from our system, clearly, we will need to correct the response through a process known as equalization. You may then well ponder, if the audio band is taken as 20 Hz to 20 kHz, why not simply put a single 20 dB/decade pole at 20 Hz on the consumer side, cut the record master at constant amplitude across the whole audio band and be done with it. Alternatively, why not simply cut the record at constant velocity across the audio band?

There are a few reasons why this is not done. Firstly, on the cutting head side, with constant velocity grooves, the physical amplitude modulations (i.e. music information) at HF would be too small to track accurately and further, buried in the disc surface noise. Additionally, it is likely that because these modulations would be so small, they would easily be damaged by the pick-up, resulting in loss of HF information. This, by the way, was a fundamental problem with the old, heavy pickups from the 1930's and 40's and one of the reasons the signal was bandwidth limited to about 6 kHz. Further, if the grooves were indeed cut at constant amplitude across the whole audio band, the gain range (and indeed as already intimated, the modulation range of the groove itself) would cover 3 decades, or 60 dB. Such high gain and physical modulation ranges on the media invite noise problems at HF and issues with LF content related to record warp, off-centre holes, arm resonance and so forth at the low end. What if we just cut the disc flat – i.e. the same physical deflection at LF and HF? The stylus would not be able to track the groove at HF, and there would be serious problems trying to cut a master under this regime. Clearly, some trade off's and a smarter approach are required.

The solution to this dilemma culminated in the original RIAA specification published in 1954 which split the recording equalization, and therefore playback equalization, into three sections: 50.05 Hz to 500.5 Hz, 500.5 Hz to 2122 Hz and then 2122 Hz up to 20 kHz as depicted in Fig. 2. In reality, the region below 50.05Hz is a fourth band – we'll discuss that a bit further on. It should be noted that it took about 10 or 15 years of toing and froing within the industry and a standards battle between Columbia and RCA Victor before the industry finally settled on the RIAA specification - this was not something that emerged from a single meeting of engineering folk.

Referring to Fig.2, from 50.05 Hz to 500.5 Hz, the record groove (purple trace) is cut at *constant amplitude*, which means the *velocity derived signal* on the pick-up side increases at 20 dB/decade starting at 50.05 Hz and going up in frequency to 500.5 Hz. The centre band between 500.5 Hz and 2122 Hz is cut at constant velocity, which means that *physical deflection the groove* on the disc *decreases* at 20 dB/decade from 500.5 Hz to 2122 Hz which yields a constant amplitude output from the pick-up. Above 2122 Hz, the groove modulation returns to *constant amplitude*, so the output from the pick-up cartridge *rises* with respect to the mid-band gain at 20 dB/decade.

On the playback EQ amp (Red trace), going from 500.5 Hz down in frequency to 50.05 Hz, the gain increases (relative to the mid-band) at 20 dB/decade. The gain in the 500.5 Hz to 2122 Hz mid-band is usually set to between at 30 ~ 40 dB (design implementation dependent) and is constant. Beyond 2122 Hz, the gain drops off again with respect to the mid-band at 20 dB/decade. The overall result after the input signal has passed through the RIAA EQ stage is the green trace, which is flat with frequency.

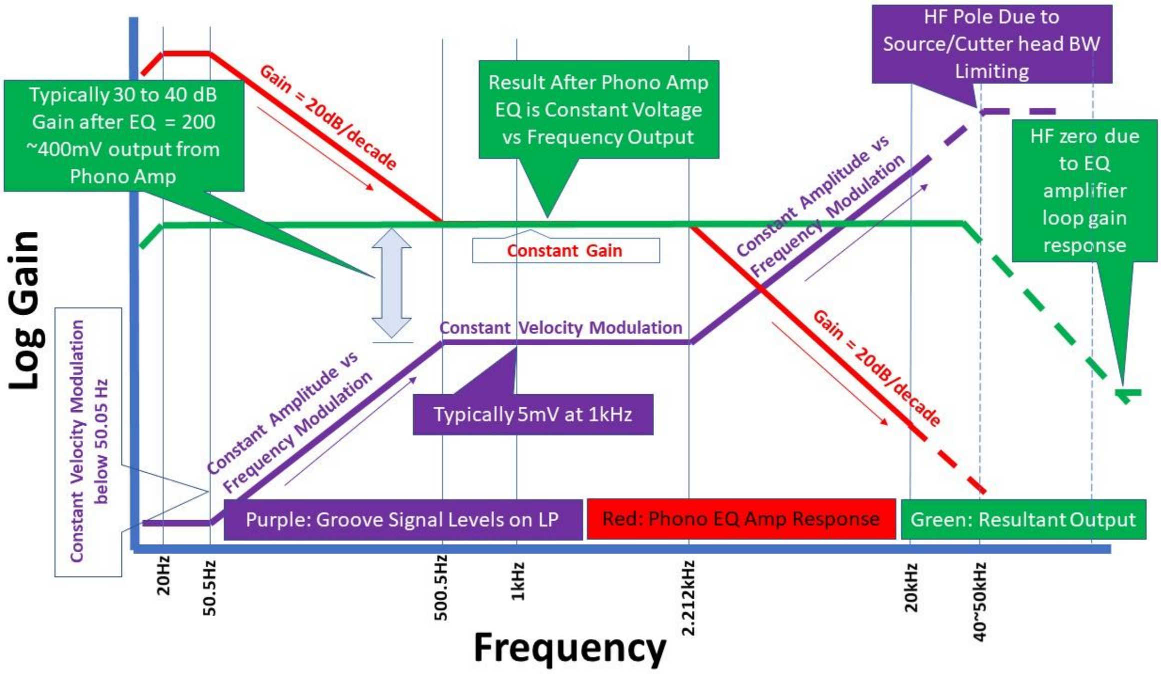


FIGURE 2 - RIAA PHONO EQ STANDARD EXPLAINED GRAPHICALLY

On the EQ amplifier, there is a further breakpoint at 20 Hz which was introduced as an amendment some years after the original RIAA specification in an attempt to address motor rumble, arm resonance and offer some attenuation of off centre and warp (see later comments). This was rejected by many practitioners for reasons discussed in the Stereophile article you can link to in the references at the end of this document. You will also note in Fig.2, that there is an HF pole somewhere up at 40 kHz or so. This has nothing to do with the 50 kHz 'Neumann pole' story circulating around the DIY community – it is just there to show that the groove modulation drops off at HF because the source signal is band width limited, and the cutting head amplifiers were also bandwidth limited (more information in the Stereophile article). There is no 'Neumann' pole and there is no useful information in any modern recording above 40 or 50 kHz. There are some old test records and measurements that show HF energy on cymbal crashes up at 50 kHz of +2 dB reference the 1kHz level, but whether this is actually music energy, or some non-programme artefact is not clear - you can read about this in the Tomlinson Holman articles referenced at the end of this document. There is some anecdotal evidence that the differences in sound between CD, which has a steep brick wall filter at ~22 kHz, and vinyl might be down to intermodulation of the music energy above 20 kHz folding harmonics down into the audible band, but I am not aware of any definitive investigations into this. Separately, if you try to correct for the 'Neumann' pole by putting a zero in at 50 kHz, the EQ amp response will rise at HF – and that means it will be amplifying all the HF energy in the clicks and pops on your disc which is not a good idea at all. After equalizing the response between 20 Hz and 20 kHz with your RIAA amplifier, the response above ~50 kHz should gently drop off at 20 dB/decade as shown with the dashed green line in Fig. 2 – you can read a bit about why this should be the case here: Inverse RIAA Network

As pointed out by others in the field, the final RIAA EQ specification was very, very well thought through and the fact that it quickly became adopted as an international standard and is still used today is testament to this. For a more in depth look at the subject, and the history, Gary A. Gallo's "Disc Recording Equalization Demystified" linked to in the reference section of this document is a wonderful reference.

It turns out that the equalization requirements on the pickup side happen also to help us in terms of HF noise caused by both the pickup amplifier and surface noise on the record itself. Because the output above 2122 Hz is attenuated at 20 dB/decade *with respect to the mid-band*, the amplifier and record surface HF noise are also attenuated by the same amount. The result is, in an all active design such as this one, an altogether quieter amplifier. At the low end of the spectrum, below 500 Hz, the signal is boosted and here we do have to be careful about hum ingress – but this is a relatively easy problem to solve with good PCB layout and construction techniques – for example, keeping transformers and motors well away from the circuit.

What about rumble, warp, or off-centre records? Record warp of course is always a problem and there is little you can do about this other than to incorporate a subsonic filter with a steep cut-off below 20 Hz and there are record presses available which allow you to flatten warped records. Insofar as rumble and off-centre records go, both issues are very much a rarity with decent modern turntables and pressings. The upshot of this is that if you are playing records that are in reasonable condition, you are unlikely to ever encounter any of these problems in real use.

And that, in short, is how the RIAA equalization recording and play back chains work in perfect harmony to get the sound out of your speakers. That an electro- mechanical system, with tiny pick-up signals of around 5 mV at 1 kHz and some serious equalization on both the record and play back chains works so well is a miracle. And work well it does. If you are used to the 'perfect sound forever' of CD's and digital music sources and not familiar with records, you will certainly be impressed with the sound of vinyl.

A Word About Noise Performance

The noise performance in any RIAA phono amp is limited primarily by the inductive reactance of the cartridge coils. The pick-up coils appear in parallel with the input loading resistor - almost always specified at 47k by the cartridge manufacturers and pretty much an industry standard. The coils output reactance shunts the 47k resistor and as this reactance rises with frequency, so does the Johnson noise contribution of any of the resistive elements in parallel with it plus of course the native input referred noise voltage and noise current of the active amplifying device. The NE5534A is still, 40 years after its debut, the best performing gain element vs cost available. Nothing else comes close for the less than a $ or £ they cost at mainstream distributors like Mouser, Digikey and RS Components. In this design, you can expect about 76 dB S/N ratio which is extremely quiet. For those of you who want to dig a bit deeper into this, Stuart Yaniger has created a very nice spread sheet RIAA S/N Ratio Calculator which will calculate the best S/N ratio you can achieve based on your pick-up cartridge coil inductance and DC resistance.

There are some ultra-high-performance designs that yield S/N ratio's approaching 90 dB (ref 5mV 1 kHz) but these invariably use parallel discrete JFET's that are difficult to source, most often require matching and require some very good design skills to implement successfully – I touch on this subject in 'RIAA Equalizer Amplifier Design' which is referenced at the end of this document.

Specifications

General Description

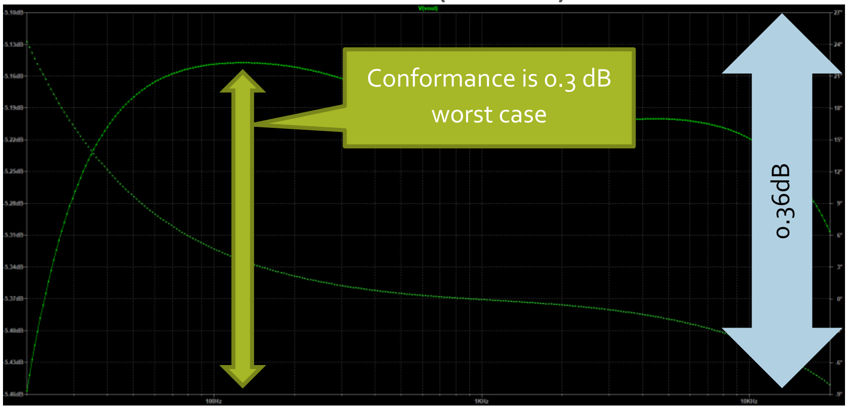
A simple, effective, high performance all-active RIAA Phono EQ amplifier using an NE5534A opamp for optimum noise, overload, and distortion performance.

Input Impedance	47 kΩs
Gain	39dB (~89x) or 33 dB (~40x); see text for details
Overload at 5mV at 1 kHz	28dB at high gain setting and 35 dB for low gain setting
RIAA Conformance 20 Hz to 20 kHz	Typically 0.3 dB at either high or low gain settings
	0.2dB with 1% EQ components (low gain)
	0.5 dB with 2% EQ components (low gain)
Signal to Noise Ratio ref 5mV at 1 kHz	76 dB (Cartridge L = 600mH and R = 600 Ohms)
Distortion	Better than 0.01% at 1 kHz and 445mV output (high gain)
Output for 5mV input at 1 kHz	445mV at high gain; 200mV at low gain
Output impedance	150 Ω in parallel with 10nF
Max Output Load Impedance	>10k Ωs and not more than 500pF capacitance
Power Supply Requirements	25 mA at +-15VDC to +-18VDC
PCB Dimensions (Phono EQ)	86mm x 66mm (stereo board) single sided
Build cost (excluding Single sided PCB)	approx. £25 ($35)
Optional PSU Build cost	approx. £25 ($35)

FIGURE 3 - MY PERSONAL TURNTABLE IS A MICHEL GYRODEC SE WITH A REGA ARM AND ORTOFON RED CARTRIDGE FITTED WITH A BLACK SHIBATA NUDE STYLUS (PHOTO COURTESY MICHEL ENGINEERING, LONDON, ENGLAND).

Performance – Graphs

FIGURE 4 - 20HZ TO 20KHZ CONFORMANCE (39DB GAIN)



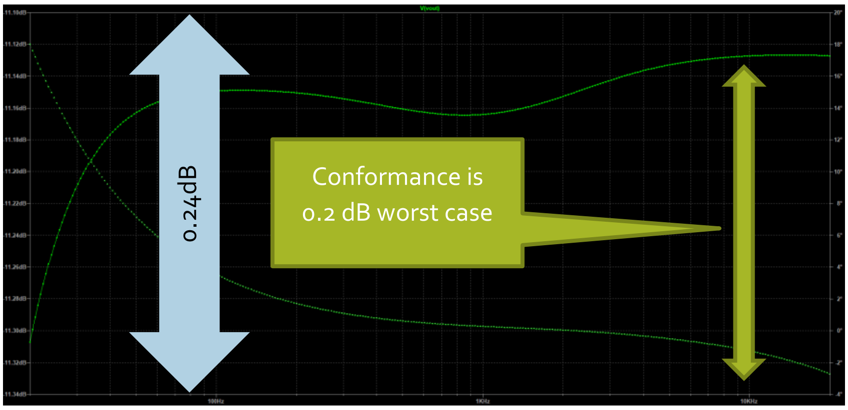


FIGURE 5 - 20HZ TO 20KHZ CONFORMANCE - 33DB GAIN

FIGURE 6 - 1HZ TO 2MHZ RESPONSE

Circuit description

Referring to Fig 7 and looking at the components around U2 (the circuit around U1 operates in the same way). The signal enters J2 and into the non-inverting pin of U3 with the input load being provided by R13 (47k). C23 (22uF 35V Bipolar) provides DC blocking to protect your cartridge should there be a catastrophic failure and DC appear on the inputs of the opamp (unlikely, but quite possible). The reason these are oversized is because it is important that the series impedance appearing at the input of U2 is as low as possible. If we used, say a 1uF coupling capacitor, the reactance at 1 kHz would be 150 Ohms and at 100 Hz about 1.5k Ohms – so below 1 kHz it would make a significant negative contribution to the overall noise performance.

U2, the ubiquitous NE5534A is the perfect match for single stage all-active RIAA phono amps like this one. Very low input noise current and low noise voltage allow this simple circuit to deliver around 76 dB S/N ratio – more than good enough to qualify as low noise. The equalization network consists of all the components within the shaded area. Standard E24 values are used throughout, making component sourcing much easier. To calculate the values, I used Prof. Stanley Lipshitz's equations which I programmed into a spread sheet - you can read a more in-depth article on RIAA amplifiers and take a look at the spread sheet here. The components in the green shaded area set the 50.05, 500.5 and 2.122kHz EQ breakpoints and R12 and C17, also within the shaded area, provide some top octave equalization to bring the overall response at 20 kHz to within 0.15 dB (typical) of the required value. R8 and R11 set the overall gain to 89x – very high for a MM EQ, but necessary if you are feeding the output into a line stage that typically on modern equipment will have a sensitivity of 1 V, or if you are using a low output MM cartridge (e.g. 3mV at 1 kHz). If you are using this EQ with a legacy line stage, the input sensitivity is likely to be around 200 mV, in which case you should remove R11 (left channel) and R4 (right channel) to drop the gain to 40x. Changing the gain in this way has minimal practical impact on the overall RIAA conformance. In any event, with this approach you have some gain flexibility which is never a bad thing.

Note that all the components in the shaded area are 1% tolerance, except for C20 (and C3 on the other channel) which are 2% types. If you can get 1% tolerance devices, or you can select for their exact values, then of course the overall conformance will be much tighter – but it is highly unlikely you will hear any difference in practice. C16, C7, C21-C24 are all 35V *bipolar* electrolytics.

Because of the output HF EQ filter (R12 and C17), the output load that this phono amp feeds into should *not be less than 10k and the load capacitance no more than 500pF* – you will hardly ever find loads as heavy as this in any domestic set up, so this design is in fact *very* load tolerant. R14 simply provides some charge bleed-off for C22 so that if you are switching between the EQ amp and other inputs, clicks and pops will be minimized.

A separate +-12 to +-18 Volt regulated power supply is required to run this EQ amp. Power is fed in via J1 with C10 and C11 providing localized bulk filtering and D1 and D2 protection for PSU reversal during power-up and power down cycles, and if you happen to accidently swap the + and – during initial wiring up. C12 to C15, which are located close to U1 and U2, provide local decoupling. C9 and C8 provide cross rail decoupling, a requirement to ensure absolute stability with the NE5534 and 5532 devices, and first highlighted by Douglas Self.

EQ Board Schematic

The single sided Gerbers and PDF's (positive and negatives) are available on the hifisonix website so you can easily etch your own boards.

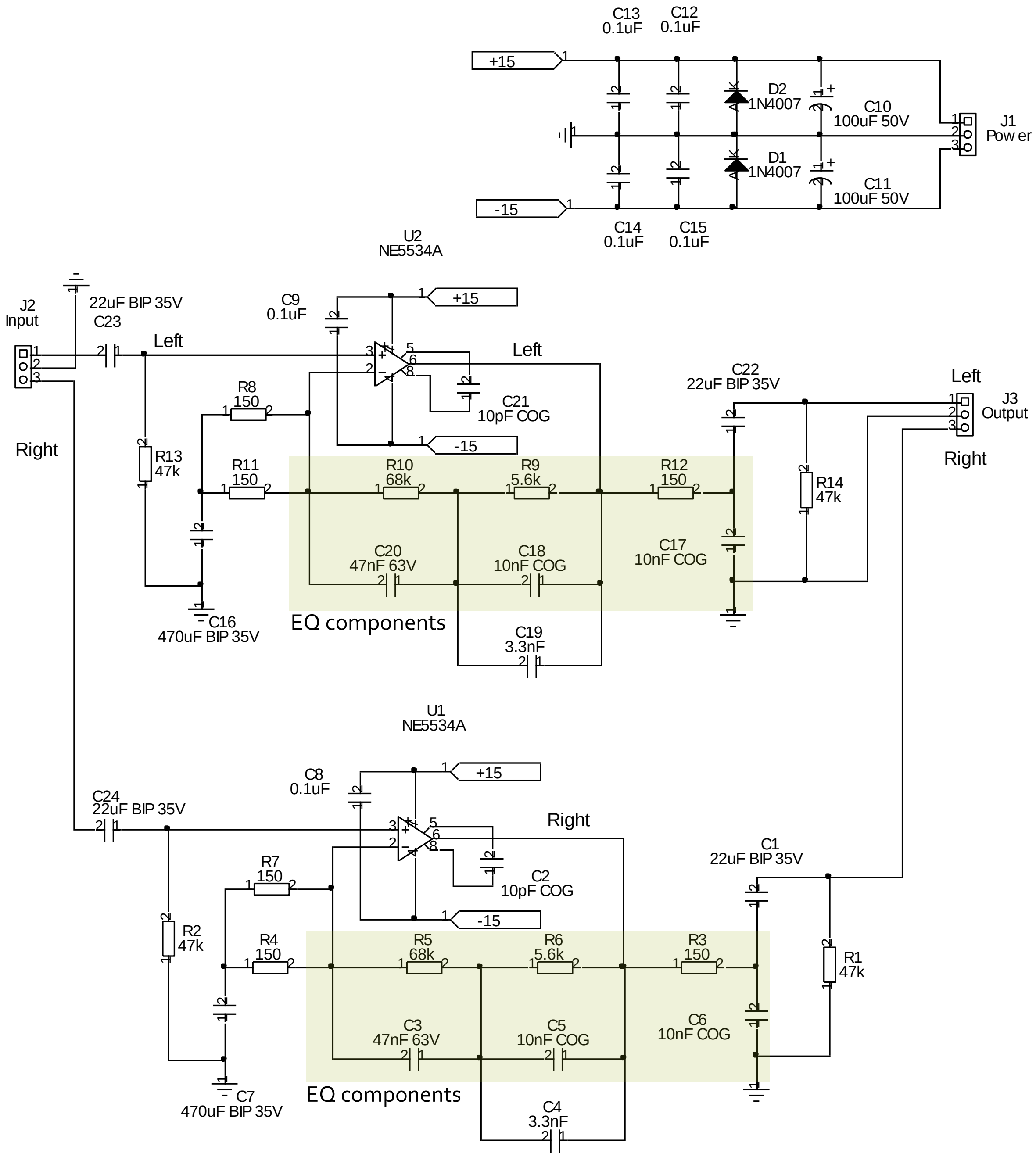


FIGURE 7 - HIFISONIX PHONO EQ CIRCUIT

Power Supply Schematic

Shown below is the circuit for a suitable ±15V at 60 mA power supply that you can use to power the EQ board. The single sided Gerbers and PDF (negative and positive) are also available on the hifisonix website so you can easily etch your own boards.

If you are retro-fitting the EQ board to an existing piece of equipment and you already have the requisite ±12 to ±18 VDC supply, you will not need this PSU – however, make sure in that case the supply you are using is well regulated and free of any noise.

Note that the EQ board will only draw 25mA max in normal operation.

Exercise extreme caution when dealing with mains!

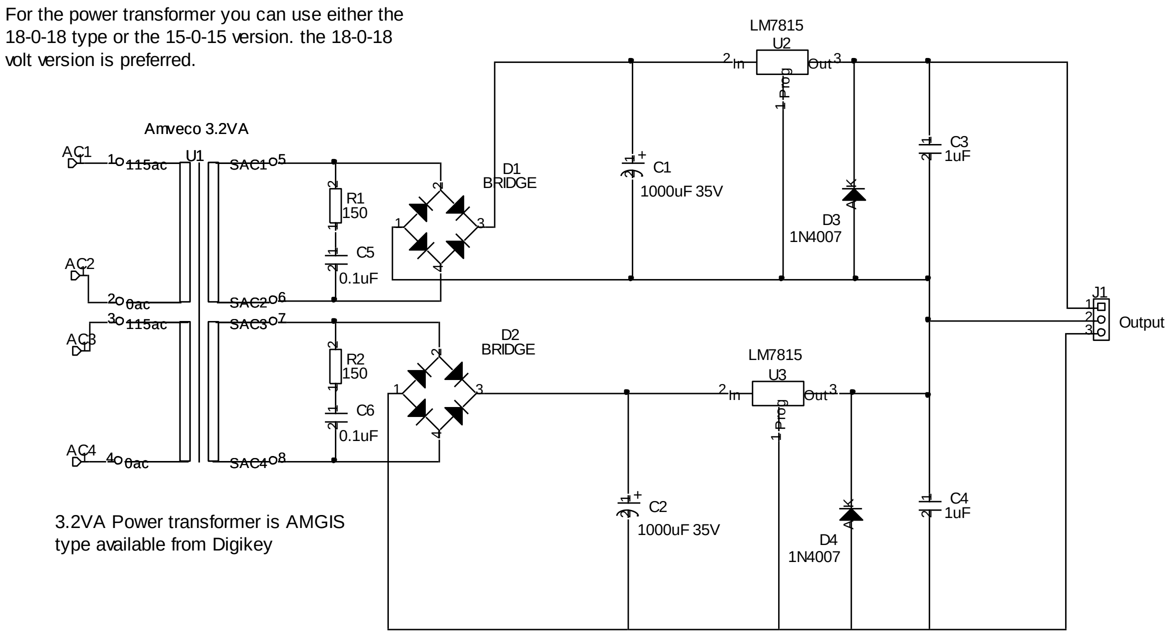


FIGURE 8 - PHONO EQ BOARD POWER SUPPLY

PCB Assembly – EQ Amplifier Board.

PCB assembly is straight forward, start with the wire links (there 6 of them) resistors, and then the capacitors and finally the op-amps.

I do not recommend you socket the op-amps and this can lead to problems in the long run. This is such a simple circuit that you are unlikely to need to remove them for any debugging, and besides, you can save yourself the expense of two costly IC sockets.

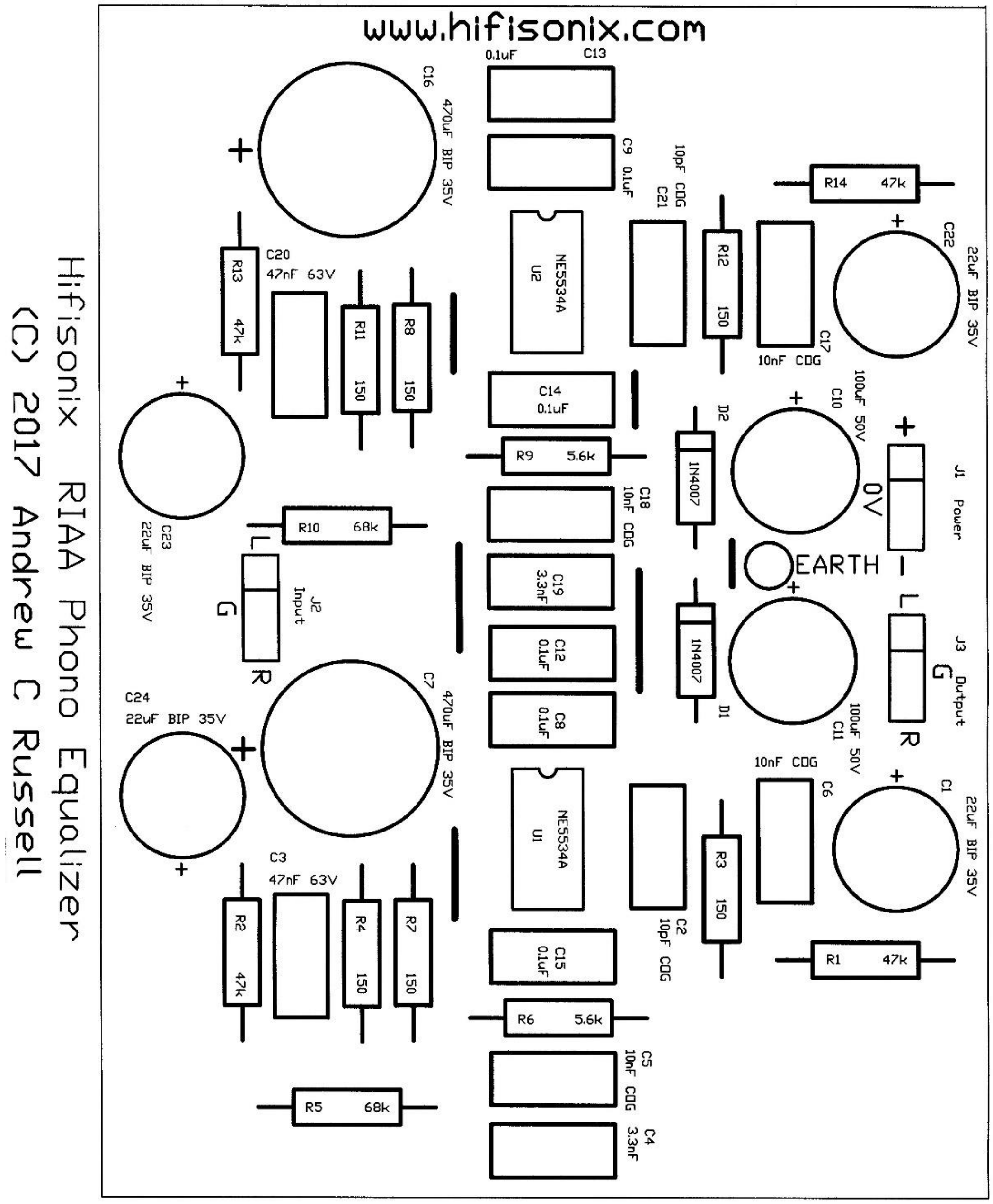


FIGURE 9 - HIFISONIX PHONO EQ OVERLAY

PCB Assembly – PSU Board.

Disclaimer: Exercise extreme caution with mains voltages. Do not attempt to build or use this power supply if you are not familiar with the safety requirements or the dangers of mains voltages!

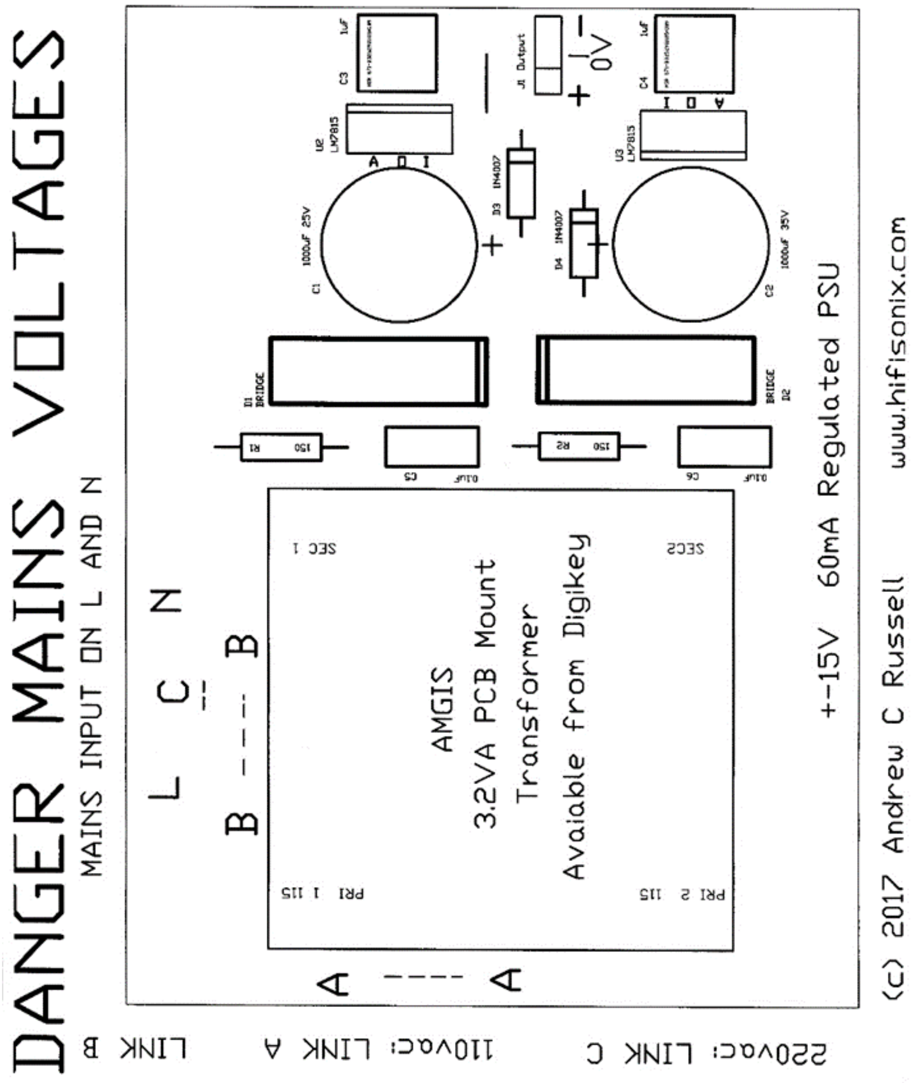


FIGURE 10 - HIFISONIX EQ PSU OVERLAY

Referring to the links marked A-A, B-B and C on the overlay above:-

<u>For 220 VAC operation:</u> link C and apply the mains voltage to L (Live/Hot) and N (Neutral) on the PCB

<u>For 110 VAC operation:</u> link A to A; link B to B; do NOT link C. Apply the mains voltage to L (Live/Hot) and N (Neutral)

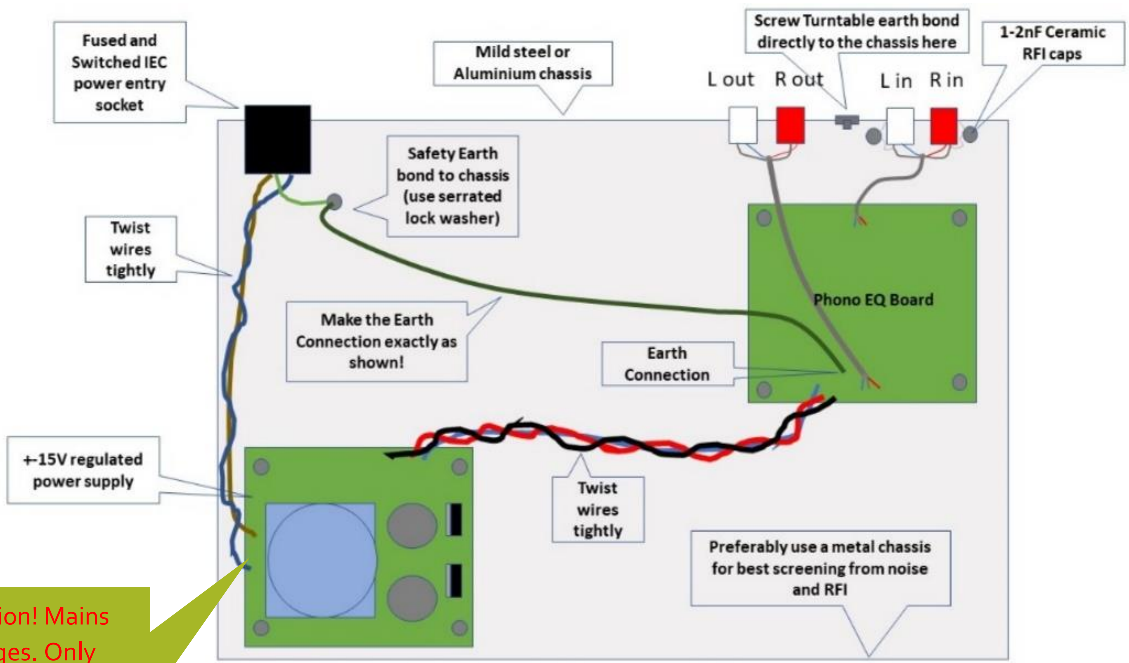
Caution: There are Mains Vloltages on the PCB. Exercise extreme care!

Wiring up

It is VERY important that you adhere to the following wiring instructions carefully. Getting superior noise and hum performance is easily achievable provided you follow these simple guidelines.

1. If you are building this as a standalone EQ amplifier, use a metal housing (mild steel or aluminium) as this will provide screening. Mild steel is preferable because it will provide some screening from LF noise.
2. Mount the EQ PCB right next to the input phono sockets – keep the wire connection as short as practicable (50 to 75mm is about right)
3. Tightly twist together the wires from each input socket to the PCB, or use decent quality braided screened cable to make the connection
4. Keep the power transformer, rectifier, and regulators WELL AWAY from the EQ PCB. Use a decent quality toroidal transformer – avoid EI types as they radiate a lot of EMI. The AMGIS type from Digikey specified in the accompanying PSU for this project is very quiet and ideal.
5. The PSU should be *__at least__* 6 inches away from the EQ board. The more the better.
6. Tightly twist the +15V, 0V and -15V wires from the PSU to the EQ board
7. Tightly twist the output left, right and signal ground wires from the EQ board to your line stage, or output sockets, *or* use good quality2 core screen cable
8. Make sure the input and output sockets, if you are using them, DO NOT connect to directly to the metal chassis
9. Wire a 1-2 nF ceramic capacitor from each phono input socket signal ground to the metal chassis right at socket. Keep the capacitor leads as short as possible. This will prevent RFI from entering the housing.
10. Note there *__one, and only one,__* Safety Earth (Safety Ground) connection to the chassis

The diagram below gives you some idea of how to do it so you end up with zero hum and noise.



!Caution! Mains voltages. Only wire up mains circuits if you are familiar with the safety requirements!

FIGURE 11 - GENERAL LAYOUT GUIDELINES FOR MINIMUM NOISE

EQ Board BOM

Item	Count	Label-Value		Designation
1	4	22uF BIP 35V	647-UVP1V220MED	C1,C22, C23, C24
2	2	10pF COG	80-C322C100K5G	C2,C21
3	2	47nF 63V	594-2222-416-44703	C3,C20
4	2	3.3nF	810-FA28C0G1H33200	C4,C19
5	4	10nF COG	80-C330C103G5G	C5,C6,C17,C18
6	2	470uF BIP 35V	647-UVP1V471MHD	C7,C16
7	6	0.1uF	505-MKS2C031001A00MC	C8,C9,C12,C13,C14,C15
8	2	100uF 50V	647-UVR1H101MPD1TD	C10,C11
9	2	1N4007	na	D1,D2
10	1	Power	na	J1
11	1	Input	na	J2
12	1	Output	na	J3
13	4	47k	AXIAL0.5 Ressistor	R1,R2,R13,R14
14	6	150	AXIAL0.5 Ressistor	R3,R4,R7,R8,R11,R12
15	2	68k	AXIAL0.5 Ressistor	R5,R10
16	2	5.6k	AXIAL0.5 Ressistor	R6,R9
17	2	NE5534A	595-NE5534AP	U1,U2

You will need **one** PCB only for both channels.

All part numbers above are from Mouser. Where part numbers are not shown, any good quality devices can be used.

PSU BOM

Item	Count	Label-Value	Mouser PART NUMBER	Designation	NOTES
1	2	1000uF 35V	647-UVR1V102MHD	C1,C2	
3	2	1uF	80-R82DC4100AA60J	C3,C4	
4	2	0.1uF	505-MKS2C031001A00MC	C5,C6	
5	2	BRIDGE	750-KBL404-G	D1,D2	
6	2	1N4007	na	D3,D4	
8	2	150	NA	R1,R2	
9	1	AMGIS 3.2VA Transformer	DK TE2231-ND	U1	Supplier is DIGIKEY
10	2	LM7815	511-L7815CV	U2,U3	

All part numbers are from Mouser, except for the AMGIS transformer (Digikey). Where part numbers are not shown, any good quality devices can be used.

References

1. Keith Howard writing in Stereophile: The Cut and Thrust of LP Equalization
2. Douglas Self: Small Signal Audio Design (2010) pages 161 through 216
3. Hifisonix: RIAA Equalizer Amplifier Design
4. Turntablehistory.com
5. Garry A. Gallo "Disc Recording Equalization Demystified"
6. Tomlinson Holman "Dynamic Range Requirements of Phonographic Amplifiers" 'Audio', July 1977
7. Tomlinson Holman "New Factors in Phonograph Preamplifier Design" AES Reprint, 1976

Document History

Initial Release	January 2018