X-Altra Moving Coil/Moving Magnet RIAA EQ Preamplifier (Part 1)

Design Overview and MC Preamplifier

For this DIY project, Andrew Russell shares the X-Altra Phono EQ Preamp, which is an accurate, very low noise high-performance phono equalizer that will accept moving coil and moving magnet inputs.

By
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The X-Altra phono preamplifier can be used with both Moving Coil (MC) and Moving Magnet (MM) pickup cartridges and separates the MC and MM input circuits to optimize overall noise performance. It features an ultra-low noise LSK389B JFET from Linear Systems in the MM front end with switchable gain and resistive loading. The MC front-end utilizes "current injection" input stage with Zetex ZTX851/951 bipolar devices for use with cartridges down to 3Ω coil resistance.

The MC preamplifier stage is best suited to cartridges with output currents in excess of 12µA. The design incorporates a 20Hz high-pass filter that can be switched to 45Hz to reduce "acoustic" rumble evident on some classical recordings. Surface-mount device (SMD) components are used extensively, and the result is a compact unit that fits into a Modushop "Galaxy" half-width housing. All DIP switch settings are accessible on the unit's rear panel (**Photo 1**).

PCBs are available should builders wish to try out the design. The rear panel is made from drilled and milled double-sided, matt-black silk screened and gold-plated THP PCB, which replaces the aluminum rear plate supplied with the Modushop housing.

A complete unit will cost about $300 to $350 in construction costs, including the housing and PCBs (**Photo 2**).

Phono Preamplifier Design Considerations: Noise and Overload

A MM source poses a number of design challenges with respect to noise, where there are three major thermal noise sources to consider: the amplifier's noise voltage, its noise current, and thermal noise of the real resistive part of the source impedance. The cartridge can be modelled as an inductor of between 400mH and 800mH in series with a (typically) 500Ω to 1.5kΩ resistor—the figures are dependent upon cartridge make and model, which is usually loaded with 47kΩ and between 100 pF and 200pF arising from cable capacitance. At low frequency, the input referred noise source impedance is simply the generator resistance shunting the 47kΩ load resistor and any high performance op-amp (e.g., an AD797 or a LT1115) would achieve around -75dB to ~76dB signal-to-noise ratio (SNR) ref 5mV. However, the cartridge impedance rises quickly with frequency so that by 20kHz, it is as high as 15kΩ to ~20kΩ.

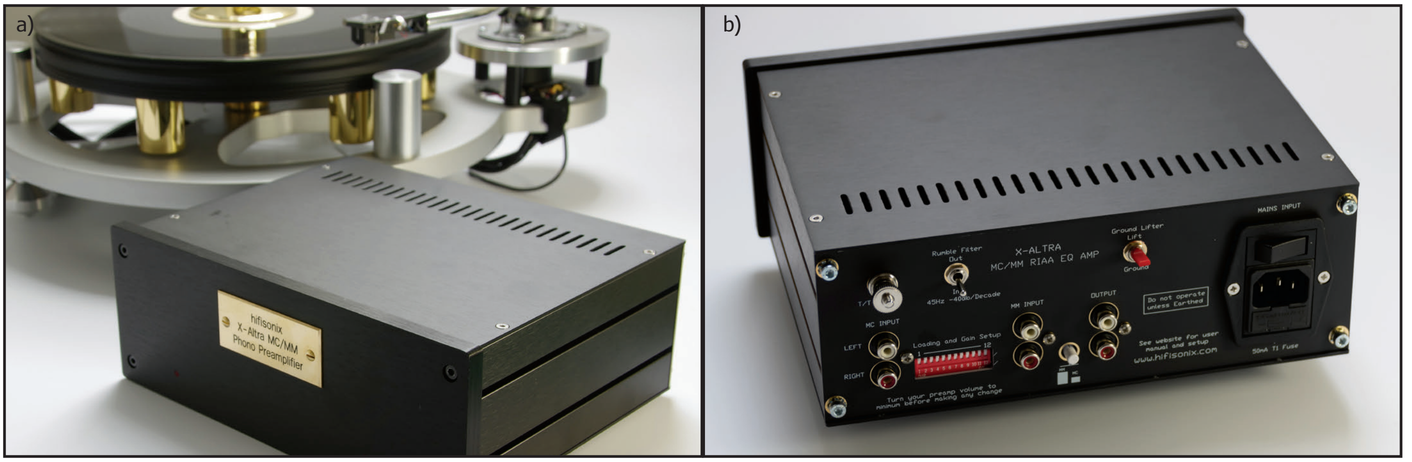

Photo 1: The X-Altra RIAA design incorporates a 20Hz high-pass filter that can be switched to 45Hz to reduce "acoustic" rumble evident on some classical recordings (a). SMD components are used extensively. All DIP switch settings are accessible on the unit's rear panel (b).

This shunts the 47kΩ input load resistor, so at 20kHz the amplifier sees a source impedance around 10kΩ to ~15kΩ, rather than just the DC resistance of the pickup coils, which is the case at low frequency. The amplifier input noise current flowing through this source resistance gives rise to a noise term that adds RMS style to amplifier input noise voltage and the thermal noise voltage of the generator resistance itself.

In a MM bipolar input amplifier, noise current flowing through the input source impedance quickly limits achievable noise performance. In a typical cartridge with a DC resistance of 1350Ω and L = 500mH (which I will refer to as the standard cartridge for the rest of this article), the total integrated noise over the audio band is approximately 3.1µV RMS or about 20x more than an op-amp such as an AD797 fed from a low-source impedance. One of the reasons the 40-year-old bipolar input NE5534A (the teal trace shown in **Figure 1**) remains so successful as a general-purpose MM phono amplifier building block is that its input noise current is low at 0.4pA/√ Hz, which is about one quarter that of other low noise op-amps (e.g., the AD797 or the LT1115).

Junction field-effect transistors (JFET) op-amps have much lower noise currents, but input referred noise voltage is generally higher, although there are a few outstanding devices (e.g., the AD745) that are better than the NE5534A but at a significant cost premium. However, using a discrete JFET input design, even lower noise voltages can be had at the expense of a more complicated circuit.

Using a NE5534A, about the best practical noise floor achievable reference 5mV at 1kHz with an all-active EQ design and a shorted input is -77.5dB. Stuart Yaniger has produced a useful spreadsheet that will calculate the best SNR one can expect given the cartridge L, R and the amplifier R and C input loading parameters (see Resources). With our standard MM transducer -69dB ref 3mV or -72dB

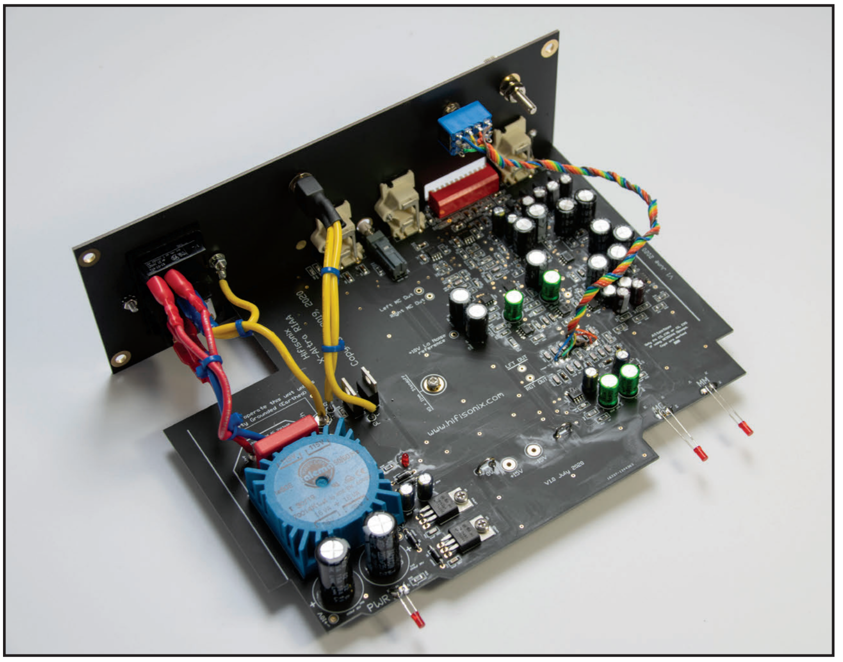

Photo 2: A complete unit will cost about $300 to $350 in construction costs, including the housing and PCBs.

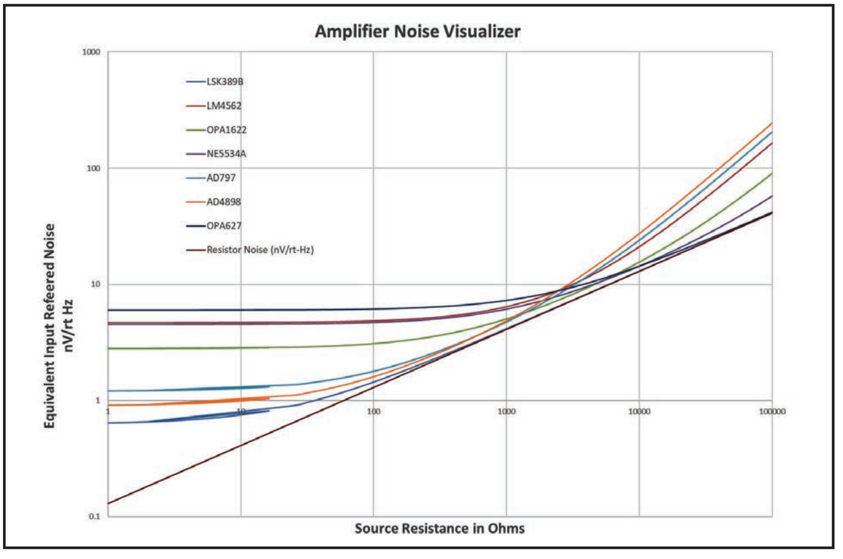

Figure 1: Selected device noise performance vs. source resistance

ref 5mV (both figures unweighted) is about all that is achievable. Using an LSK389B JFET front end with both devices wired in parallel (**Figure 2**) and a 110Ω gain setting resistor in the feedback network, a figure of -75.3dB ref 5mV is attainable in an all-active design, which is >3dB better than the NE5534A and >10dB than an OPA1602 in a similar configuration. Note: Vinyl surface noise will degrade these figures by approximately 15dB to 20dB even on a good pressing.

MC transducers feature much lower coil resistances, for the most part obviating concerns about input current noise. However, many highly regarded MC cartridges feature coil resistances of below 10Ω and outputs in the 100µV to 200µV range, and here the focus must be on minimizing the amplifier input noise voltage to get decent performance.

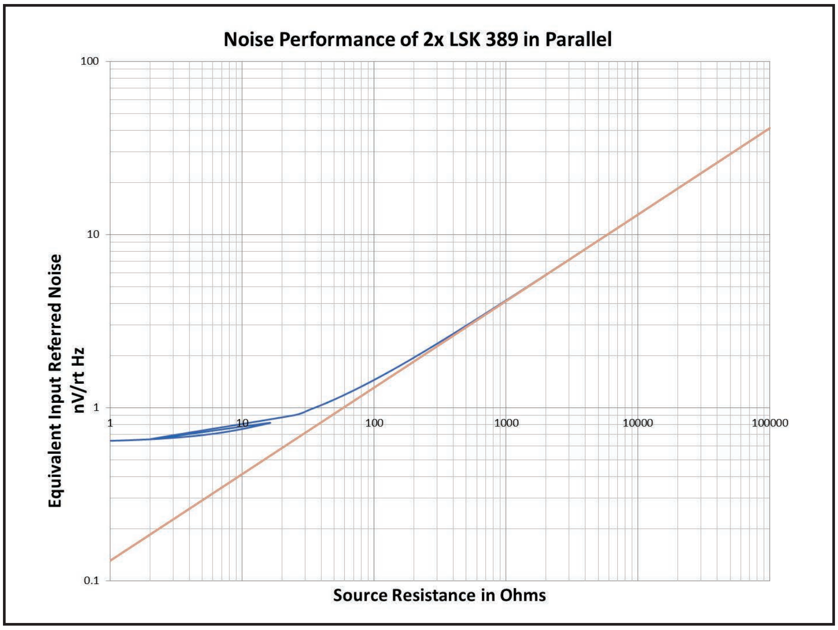

Figure 2: LSK 389 noise performance

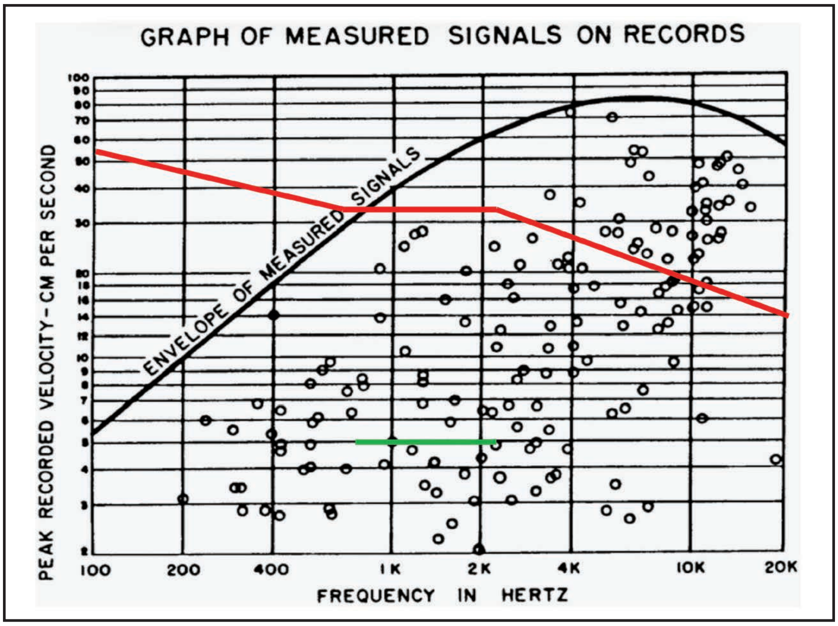

Figure 3: Peak vinyl outputs (Source: Holman, et al)

Despite a lot of effort by some very skilled participants on "Richard Lee's Ultra low Noise MC Head Amp" thread over at diyAudio, no one was able to convincingly beat the noise performance of Lee's "Duraglit Special" given the two transistors and handful of passives used in the circuit. Lee's circuit was a development of Marshall Leach's design dating back to 1978, with input referred noise in the region of 200pV/√Hz to 300pV/√Hz readily achievable, making it the go-to topology for low-source impedance generators. (Richard Lee's original head amp was built in a "Duraglit" polish tin, which was a household soft metal polish used on brass and pewter sold in the UK and hence became known as "Richard Lee's Duraglit special." Duraglit is no longer available generally.)

On both MC and MM inputs, the other area that presents a design challenge is that of overload margin. A number of papers have addressed this subject over the years, but probably the most widely cited reference is Tomlinson Holman's 1977 "Dynamic Range Requirements of Phonographic Preamplifiers," which leveraged studies from across the industry and academia. In most commercial phono preamps, gain switching in the phono stage is not provided and the only adjustment to cater for higher level output cartridges and recordings is the volume control, which is placed after the phono stage in the signal chain.

The designer, therefore, must cater to higher output transducers, "hot" recordings and the inevitable clicks and pops with their wide spectral content by ensuring overload margins of at least 25cm/sec re the 5cm/sec mid-band reference output. An extract from the Holman paper (**Figure 3**—with the green and red trace overlays added by the author) shows peak measured signals across a range of recordings with one of them achieving >70cm/sec at approximately 4kHz—a remarkable figure. Peak output signals appear to be clustered in the 2kHz to 10kHz region and 6cm/sec to 40cm/sec output range, with a few outliers higher than this as mentioned earlier.

Of interest here is many of these peak events are in the mid-band or just beyond, exposing the amplifier to high input signals at high (approximately 35dB) gain. At 50Hz and below, the equalizer gain is 20dB higher than that at 1kHz so warp and off-center records can also cause low-frequency overload problems, not shown in Figure 3 but discussed in the Holman paper. With all-active feedback and some gain switching to cater for different cartridge sensitivities, it is relatively easy to achieve >30dB overload margins on ±15V supply rails ref 5mV input levels and similarly for MC inputs ref 500µV, over 20Hz to 20kHz.

System Block Diagram

For this entire document, descriptions will refer to the left channel, the right channel being identical, other than the system power supply unit (PSU), which is shared by both channels. The key component numbers and values shown in **Figure 4** correspond to the circuit diagram component references to be discussed in depth later.

MC Front-End Amplifier

Table 1 shows there is considerable current available from a typical MC cartridge with which to develop the output voltage across a suitably configured load resistor. Since the input signal, V_{cart}, is small, and a fraction of the transistors Vbe, the distortion is low even when operating without feedback.

For a common base circuit operating in current injection mode, the idealized gain is given by:

$$V_{out} = I_{in} \times R_{load}$$

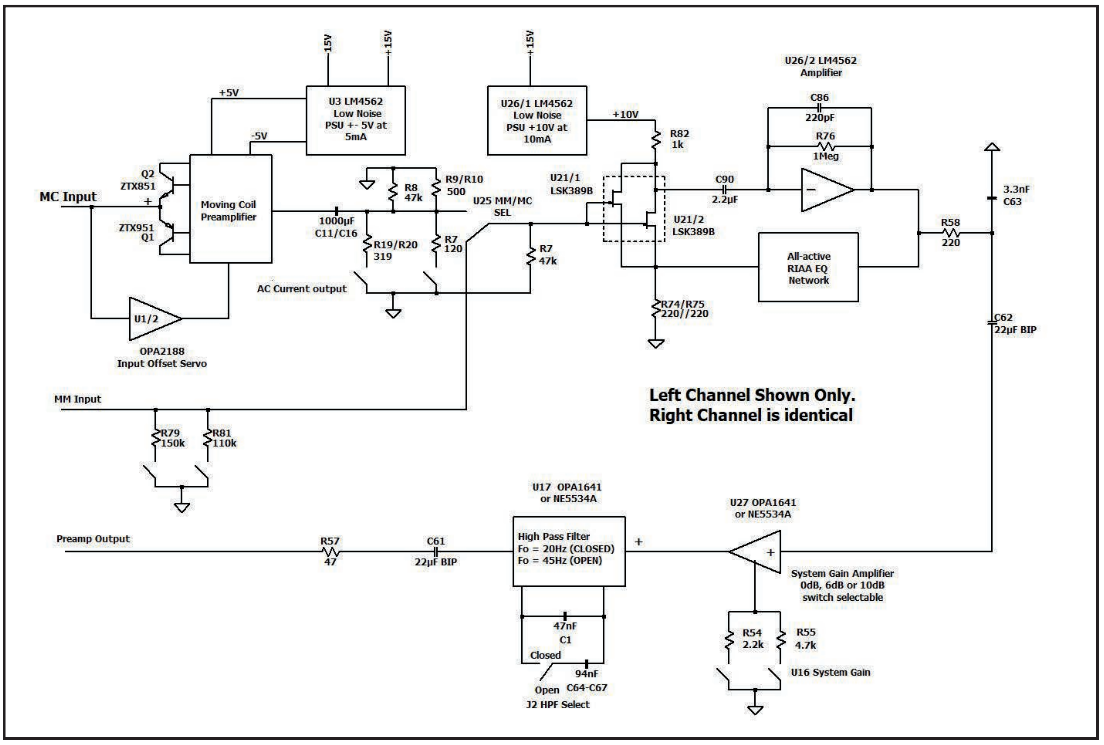

Figure 4: X-Alta block diagram

Cartridge Manufacturer and Model Number	Cartridge DC Resistance	Cartridge Output	Preamp Input Current, Including Amp R_{in} Error	Reswitch Setting	Required Voltage Gain for 5mV O/P	Actual Output Voltage
Goldring Ethos	4	0.0005V	69µA@1kHz	85	10	5mV
Ortofon Kontrapunkt "b" MC Cartridge	5	0.00047V	57µA@1kHz	107	11	5mV
Ortofon MC Vivo Blue	6	0.0005V	54.1µA@1kHz	114	10	5mV
Goldring Elite	8	0.0005V	44.4µA@1kHz	146	10	5mV
Ortofon MC Anna Diamond	3	0.0002 V	32µA@1kHz	229	25	5mV
Ortofon MC Anna	6	0.0002V	21.6µA@1kHz	435	25	5mV
Ortofon MC A Mono	7	0.0002V	19.5µA@1kHz	494	25	4.8mV
Ortofon MC Windfeld Ti	7	0.0002V	19.5µA@1kHz	494	25	4.8mV
Ortofon MC 10/MkII	3	0.0001V	16µA@1kHz	494	50	4mV
Hana EL and SL	30	0.0005V	15µA@1kHz	494	10	3.7mV
Denon DL103	30	0.00039V	11.7µA@1kHz	494	13	2.9mV

Table 1: Selected MC cartridges and associated gain requirements

However, the input impedance of the amplifier, R_{in}, is not zero, and related to the internal device emitter resistance re′:

re′ = .026/Ic
where Ic is the collector current of Q1 and Q2

In this design, an Ic of 3.5mA was chosen as it provides the best compromise between lowest noise and reasonable power consumption resulting in a re′ of 7.5 Ω. Since Q1 and Q2's re′ appears in parallel to AC, the error term is 3.25Ω and not negligible in the case of low generator coil resistances. Setting V_{out} to 5mV so the MC gain is up front to maximize noise performance, the required load resistor R_{Ltot} is given by:

$$R_{Ltot} = (.005/V_{cart})\times(R_{cart}+R_{in}) \quad (1)$$

The 1kΩ resistors R9 and R10 loading the collectors from the power supply are in parallel with the 47kΩ output load resistor for AC signals providing a pre-load of 494Ω, so we need to subtract this from the calculated R_{Ltot} to arrive at the (nearest) U2 switch load resistor setting:

$$1/R_{switch} = 1/_{RLtot} - 1/494 \quad (2)$$

Table 1 lists some MC cartridges, their output voltages, coil resistances, and resultant output currents along with the desired gain for 5mV output. If a cartridge is not listed in Table 1, apply the formulas in (1) and (2) to find the required R_{switch} to select the closest value with the DIP switches. Note that the gain can be further optimized by changing the system gain amplifier settings (discussed in Part 2 of the article), which would, for example, be required for the Denon DL103 and the Hana EL and SL cartridges to raise the overall preamplifier output. The maximum gain achievable is when the MC gain setting resistors (DIP Switch U2) are in the OFF position and the output gain setting load 494Ω.

Referring to **Figure 5a** left hand channel, the input signal feeds into Q1 and Q2 (Zetex ZX851 and ZX951), which are configured as a complementary common base pair. These devices are currently the lowest noise small signal packaged devices available with r_b′ independently measured and verified by a number of contributors on the Internet at 1.33Ω and 1.4Ω, respectively. In this design, that translates to an input referred 1kHz spot noise for the amplifier of 210pV/√Hz simulated or about one-quarter that of an ultra-low noise op-amp like the AD797, and a total integrated RMS noise over the audio band of 30nV RMS.

The common base configuration shown contributes no noise referred to the input signal other than r_b′. Because low output MC generator

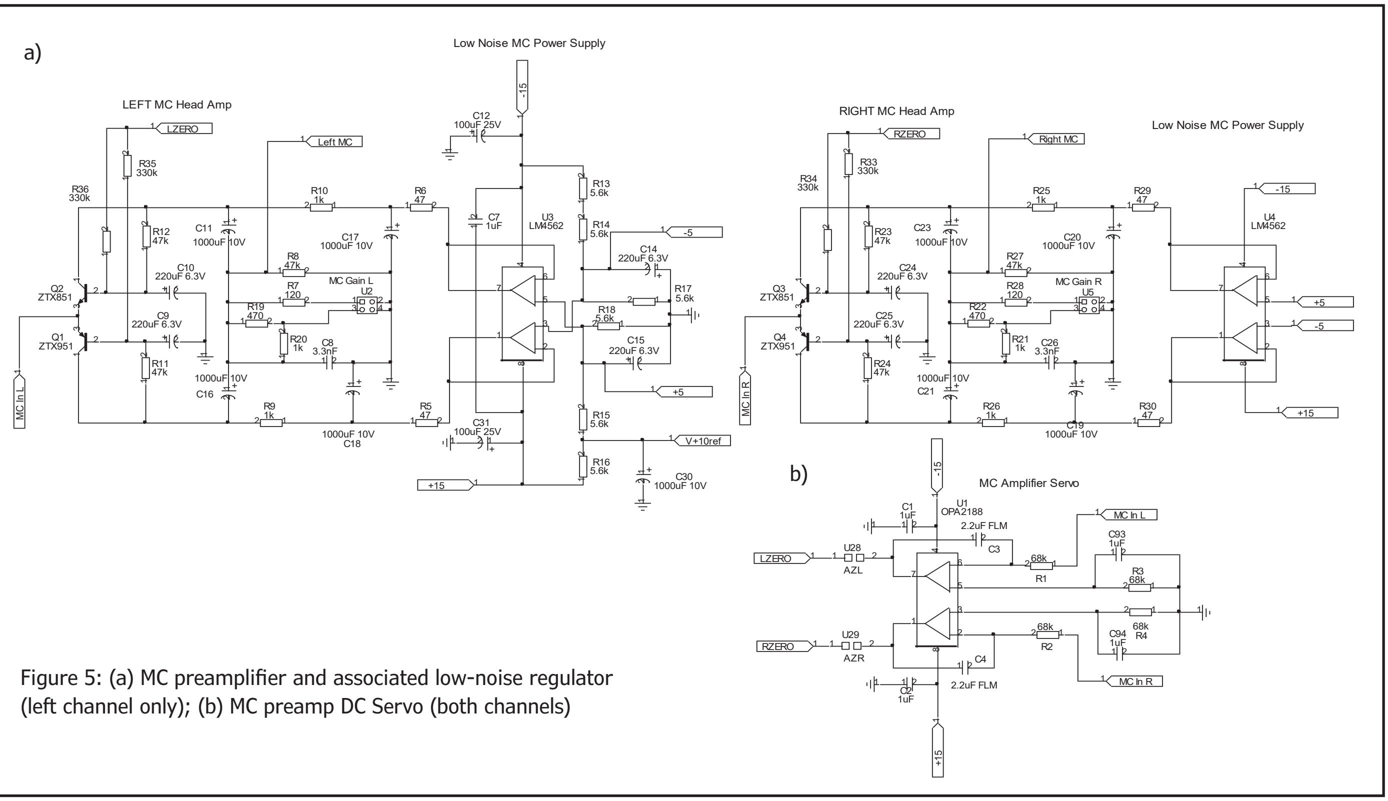

Figure 5: (a) MC preamplifier and associated low-noise regulator (left channel only); (b) MC preamp DC Servo (both channels)

resistances are generally not more than 10Ω, the noise current contributes little to noise performance, unlike the MM amplifier stage. R11, R12 set up the transistor collector current to around 3.5mA and C9 and C10 provide filtering and short the bases together at AC.

R7, R8, R19, and R20 combine the output signals from the collector load resistors R9 and R10 via C11 and C16 and provide loading adjustment via a two-way DIP switch U2 (MC Gain L) allowing the load resistor to be set to 66Ω, 83Ω, 194Ω, or 494Ω (the parallel combination of R9, R10, and R8). The output is then routed to the source selector switch U25.

The power supply rejection ratio (PSRR) of the MC head amplifier is zero. Rather than a discrete capacitance multiplier or a high capacitance RC filter, this approach leverages the outstanding PSRR of the LM4562 (U3), which at 200kHz and a 600Ω load exceeds -80dB while at low frequency, the figure approaches -110dB.

The U3 PSU reference voltages (also used by the right-hand channel regulator) are derived through the divider network comprising R13 through R18 and associated noise filtering provided by C14 and C15. The output filter comprises C17 and C18 with resistors R5 and R6 further attenuating noise from the regulator. The capacitors have been oversized so that their equivalent series resistance (ESR) is low—anything more than a few ohms will contribute excessive thermal noise to the supply rails.

Simulations indicate a 1kHz spot noise of approximately 50pV/√Hz per rail or about 7nV RMS wide band noise. For the **Figure 6** plot, the input reference voltage 220μF filter capacitor ESR was set to 600mΩ and the 1000μF output decoupling capacitor to 140mΩ—both reflective of readily available components at reasonable cost.

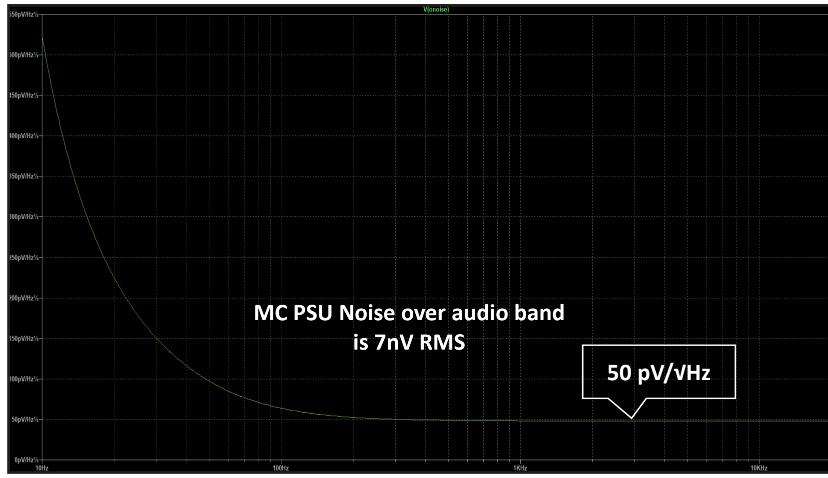

Figure 6: LM4562 power supply's simulated output noise spectral decay density

Figure 7 shows the measured noise floor of the full MC plus MM preamplifier signal chain. The QA 401 noise floor is at around -155dBV on these plots. At 50Hz, the red trace the gain is 76dB, at 1kHz 56dB and at 20kHz, 36dB. The measured input referred noise on the red trace at 1kHz is approximately 220pV/√Hz vs the simulated figure of 210pV/√Hz.

The input offset voltage as measured at the junction of Q1 and Q2 emitters can be as high as 30mV due to normal Vbe parameter spreads between the two transistors. In the battery-powered version, the power source is floating and no offset current flows through the cartridge coil; with a ground referenced supply that is not the case. An OPA2188 based servo (U1, Figure 5b) adjusts the bias on the bases of Q1 and Q2 via R35 and R36 (330kΩ each), forcing the input voltage to 0µV. The connection to the servo control point is by means of two flash pads U28 (left channel) and U29 (right channel).

During test and setup, the offset voltage is measured between the signal input and the signal ground at the input connector, which is typically 5mV to 15mV. After this, the pads are flashed closed and the offset then measured again which should be zero. I used a DVM with a 200mV FSR and was unable to resolve any offset, which is specified at ±6µV typical for the OPA2188 (±25µV maximum). It is important that the measurements are taken with the 0V reference right at the input connector as even a 1mV drop across the 0V rail will cause a severe reading error. The output of the servo amp (pins 1 and 7 on U1) once engaged should not exceed about ±6V, allowing the servo amp to output an additional ±6 V control range.

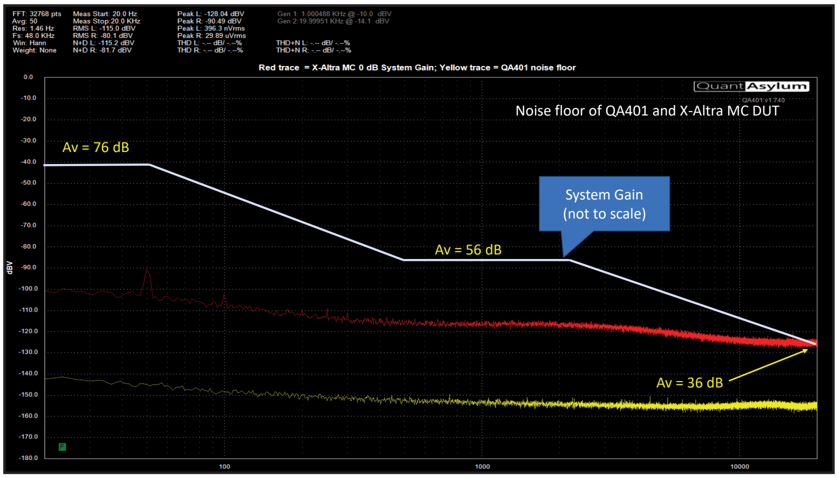

Figure 7: MC preamplifier self-noise

About the Author

Andrew C. Russell worked for the first half his career in the electronics industry in product development, qualifications and marketing, During the second half of his career, Russell was in business management and business development in the semiconductor industry working for a global MNC, spending the last 10 years based in Japan, Taiwan, and China. He struck out on his own in 2015, founding Ovation High Fidelity and doing freelance audio design consulting and contracting with an emphasis on power amplifiers and preamplifiers. When not working in his lab, he can be found walking his dog or enjoying his vinyl collection.

Next Month

Part 2 of this article will discuss the MM stage design, the system gain amplifier, the filters, and the measurements.

Project Files

To download additional material and files, visit audioxpress.com/page/audioXpress-Supplementary-Material.html

Resources

P. Baxandall "Noise in Transistor Circuits," *Wireless World*, 1968.

D. Colin, "The LP797 Ultra Low Distortion Phono Preamp," *audioXpress*, September 2007.

diyAudio "Mechanical Resonance of MMs," February 2017, https://www.diyaudio.com/forums/analogue-source/303389-mechanical-resonance-mms.html

G. A. Galo "Disc Recording Equalization Demystified," *The LP Is Back!*, The Audio Amateur, 1999, https://audioxpress.com/news/disc-recording-equalization-demystified

T. Holman "Dynamic Range Requirements of Phonographic Amplifiers" *Audio*, July 1977.

T. Holman "New Factors in Phonograph Preamplifier Design" Audio Engineering Society (AES) reprint, October 1975

"Very Simple, Accurate RIAA Phono EQ Amp," Hifisonix.com, January 2018, http://hifisonix.com/riaa-phono-eq-amp

K. Howard, "The Cut and Thrust of LP Equalization," *Stereophile*, April 2009.

W. M. Leach, "Head Amps for Moving Coil Cartridges," Georgia Institute of Technology, 1999 (original design from 1978), https://leachlegacy.ece.gatech.edu/headamp

S. Lipshitz, "On RIAA Equalization Networks," *Journal of the Audio Engineering Society* (JAES), Volume 7, Issue 6, pp. 458–481, June 1979.

"RIAA Equalizer Amplifier Design," Hifisonix.com, July 2018, http://hifisonix.com/riaa-phono-equalizer-amplifiers.

"Richard Lee's Ultra-Low Noise Head Amp" thread, diyAudio, June 2019, https://www.diyaudio.com/forums/analogue-source/339246-richard-lees-ultra-low-noise-mc-head-amp.html

D. Self, *Small Signal Audio Design*, Focal Press; 3rd edition, April 2020.

S. Yaniger, "RIAA Noise Calculator," SYclotron Audio, January 2012, https://syclotron.com/riaa-noise-calculator