m900 Technical Discussion and Design Philosophy

Grace Design has been designing and building world class audio electronics for 25 years. During that time our amplifiers and converters have been used to make thousands of amazing recordings and chances are some of the music in your collection was produced using a Grace Design circuit. Throughout our history we have continuously developed and refined design techniques that result in transparent and extremely detailed products that are bomb proof reliable and stand the test of time. Our products tend to not be classified as "clinical" or "analytical" but instead "revealing" and "invisible". Whether for the professional sound engineer or devout music fan, our products deliver high resolution, non fatiguing performance that you can depend on.

The Grace Design m900 headphone amplifier/DAC represents a new level of performance for small form factor USB bus powered devices. From the headphone amplifier, to the DAC, to the power supply, the m900 has been designed with innovations in all areas that yield truly world class audiophile performance from a compact and modestly priced package. Although the m900 is solid state, it has the non-fatiguing warmth of a tube amplifier paired with the detail, clarity, and dynamics of precision solid state design. This document is a discussion of our design philosophy and the significant technological advances made in the m900 to achieve this.

There are many factors that determine the sound quality of an amplifier / DAC design. While a particular DAC or amplifier part number play a role in this, the design of the rest of the system can have an equal or greater impact on the final sonic performance. The real quality of a design comes from how well critical areas of clocking, grounding, pcb layout, power supply design, passive component selection, EMI/RFI management, etc... are handled. Throughout development, measured performance metrics are used as inputs to design decisions, but in the end sound quality and listening enjoyment trump test equipment data. It is the cumulative and holistic approach that we believe results in a final product which the owner will enjoy for many years.

Analog Circuit Design

The m900 analog circuitry represents our cumulative knowledge of 15 years of building reference quality headphone amplifiers. From the model 901, m902, m903, and m920 headphone amplifiers, the m900 is the latest generation that delivers immaculate clarity and definition in an affordable, compact design.

Transimpedance Amplifiers

The headphone output driver is a transimpedance, or "current feedback" amplifier, which has several important advantages over traditional "voltage feedback" op-amps.

First, transimpedance amplifiers have a nearly constant bandwidth over a wide gain range and are not prone to large-signal slew rate limiting, which results in improved dynamic performance. The headphone amplifier in the m900 is the THS6012, which has a slew rate of more than 900V/µS. Compared to voltage feedback op-amps (which are found in most amp designs), transimpedance amplifiers have better dynamic performance and are able to track complex harmonics without adding any metallic or "solid-state" character to the sound.

Also, transimpedance amplifiers reveal greater detail and provide a more open, natural sound quality. Furthermore, transimpedance amplifiers maintain the same sound quality at low or high gain levels.

The instantaneous nature of current feedback allows transimpedance amplifiers to have very low TIM (transient intermodulation distortion). TIM does not sound pleasing even in small quantities and occurs in voltage feedback opamp circuits when an amplifier becomes slew rate limited. The trade off here is that while transimpedance amplifiers have higher measured harmonic distortion (THD) than voltage feedback designs, these harmonic distortion components are correlated with the signal and are much more euphonic than TIM. We believe that this sound quality advantage greatly outweighs the minor measurement disadvantage.

Zero Ohm Output Impedance

The m900 headphone amplifier is built around the TI THS6012 transimpedance / current feedback amplifier. We configure this amplifier in a proprietary circuit topology that allows the ultra-high resolution, clarity, and dynamic performance of a current feedback amplifier, with the control and damping factor of a zero output impedance power amplifier. While typical implementations of high speed transimpedance amplifiers require 10Ω or higher output impedance, the m900 measures 0.080Ω, making it unique among headphone amplifiers on the market.

The damping factor is an amplifier's ability to damp the back emf (electro motive force) from the headphone transducers. In essence this is the ability of the amplifier to control the diaphragm motion of the headphone driver and keep it from overshooting and ringing. A higher damping factor will result in better frequency response, lower distortion, and improved phase response. When driving 20Ω headphones, the m900 has an output damping factor of over 250. By comparison, a typical headphone amplifier with 10Ω output impedance will have a damping factor of only 3.8. With 300Ω headphones the damping factor is over 3700. The result of such a high damping factor is a sound that is very tight and controlled (especially in the bass), with exceptional dynamic impact but also excellent harmonic resolution and detail.

Some headphones have relatively flat impedance vs frequency, while others like IEMS (that contain multiple drivers and crossovers) will vary considerably with frequency. Very low output impedance and high damping factor reduces the frequency and phase response effects of headphone transducers with varying impedance.

The THS6012 is a high current amplifier specified for driving 500mA of continuous current in to a load. With the m900 in high power mode, it can deliver 440mA peak in to 20Ω loads with both channels driven which is a momentary power of 1800mW per channel. This type of load is not uncommon for low impedance low efficiency headphones such as planar magnetic types. This power capability ensures that the m900 can faithfully track dynamics and transient material without clipping or compressing.

With a 10Ω load the m900 can deliver over 750mA peak (one channel driven) which is momentary power of 2800mW. While actual headphone loads of 10Ω are rare, it is good practice to have plenty of margin above what a typical load current would be.

Whether driving miniature balanced armatures in IEMs, large over the ear dynamics, or planar magnetic transducers, the low output impedance of the m900 will help reveal the subtle detail, complex harmonics, and true dynamics of your music.

Passive components

The m900 is direct coupled which means there are no capacitors in the signal path. Capacitors are often used to block DC offset voltages from one amplifier stage to another or to keep DC offsets from reaching the output. To prevent this in the m900 the output amplifier is DC servo controlled. This technique minimizes output DC offset to negligible levels and enables the m900 to have extended low frequency response down to 0.5Hz. So not only will the m900 accurately produce the deepest bass, this also ensures that there will be no phase shift problems in the audio bandwidth.

In addition to achieving minimal low frequency phase shift, the absence of capacitors in the signal path, (especially aluminum electrolytic types) helps account for the lack of a metallic or hard sound signatures often associated with capacitor non-linearities.

In places where large capacitors are needed (in the power supplies for instance), we use only long life high temperature (2000hour/105°C) electrolytics and high grade ceramics.

All of the resistors in the circuit path are half-percent precision, 25ppm temperature coefficient, low current noise thin film types. This ensures low noise, low distortion, dynamic accuracy, as well as excellent channel matching.

The circuit board is fabricated with four copper layers, which allows ultra-low inductance, low noise ground planes and efficient routing of power supplies for the most direct path to each amplifier stage. As well, the thermal conduction of the pcb keeps temperatures stable and minimizes thermal modulation of sensitive low level circuits.

Volume Control

Volume is controlled by a hybrid system, with most of the volume control duties handled in the digital domain with 32bit processing. The output amplifier is designed to operate in two gain modes: 0dB and +10dB. These gain modes are controlled automatically to create a 99 dB volume range with 0.5dB steps. This ensures that the m900 can produce low levels suitable for the highest sensitivity IEMs and high levels required to drive low efficiency planar magnetic headphones.

32 bit processing ensures that any artifacts of volume control operations are vanishingly small at -190dB down from full scale.

Headphone Crossfeed

When listening to loudspeakers in a room, your left ear hears sound primarily from the left speaker (and vice versa) but also receives a signal from the right speaker at a lower level and with some time delay compared to the right ear. As well, the right speaker sound that reaches the left ear does not have a flat frequency response as the sound waves have traveled around the shape of your head before reaching your left ear. The brain uses delay, level and frequency response characteristics to process the location of a sound and hence, create an aural image.

When listening through headphones, each ear only hears the sound from one transducer and the mixing of signals between the ears does not exist. In this situation the brain is left without many of the psycho acoustic clues required to generate a properly distributed image and an accurate sound stage. The result is that instruments seem to cluster in the far left, far right or center of your head. Since the vital clues are absent, the brain has a difficult time deciding how to process the sounds coming from the headphone, which can result in listening fatigue when listening for extended periods of time. The m900 contains crossfeed circuitry which electronically simulates the signal crossfeed that occurs in a real acoustic space and helps the brain establish instrument locations across the entire sound stage. While it is difficult to perfectly model the very complex level, delay and frequency response characteristics of the head, the crossfeed circuitry in the m900 gives the brain some of the basic clues it needs to establish instrument locations across the entire sound stage, and the result is a very pleasing simulation of an acoustic space while maintaining the tonality and balance of the original source.

The m900 contains a completely passive analog crossfeed circuit. The crossfeed circuit is implemented with precision metal film resistors and film capacitors and is switched in and out with a sealed gold contact relay. Below is graph showing the crossfeed frequency response. This plot is of each channel's output while being driven on only one channel in.

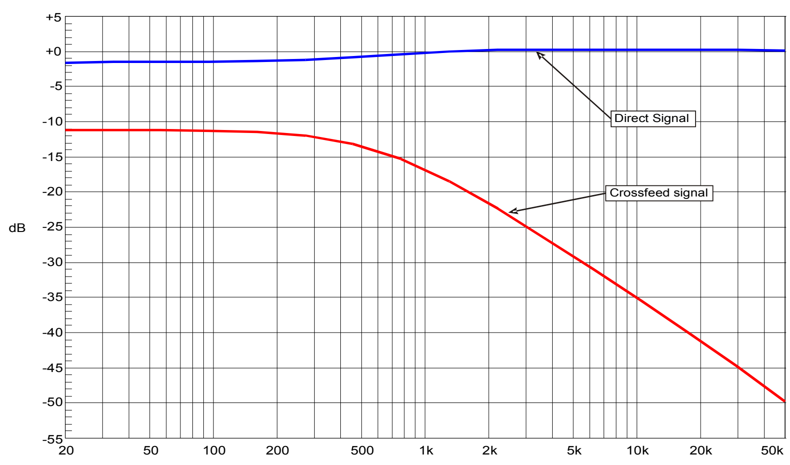


Illustration 1: Headphone Crossfeed Response

Digital to Analog Converter

The USB digital section of the m900 provides a true 32bit wide data path from the computer to the DAC. It plays sample rates from 44.1kHz to 384kHz PCM as well as 1 bit DSD64 or DSD128.

DAC Integrated Circuit (IC)

The DAC is the AK4490, which is part of a new generation of converters from AKM (pioneers in delta sigma

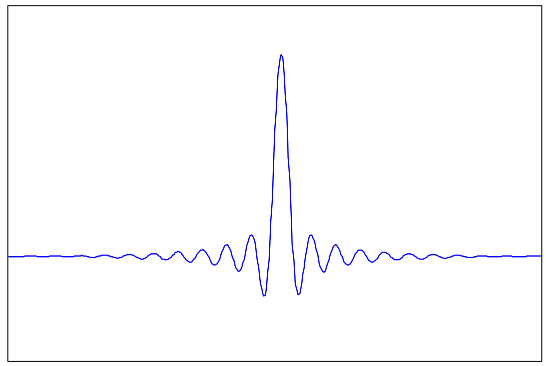
DACs and ADCs). The AK4490 is a 256x oversampling, 32bit processing DAC that is capable of 120dB dynamic range and -112dB THD+N.

Digital Filters

There are four 32bit filters to choose from depending on the listeners preference and the type of music. High amplitude signals around ¼ of the sample rate can cause inter-sample clipping in many DAC digital filters. Many modern recordings are mastered with such high levels that it is not uncommon to so see many peaks which can cause clip events. These events then cause cause large amounts of distortion. The DSP processing in the m900 is designed with enough headroom to eliminate inter-sample clipping.

Filter 1: Traditional fast roll-off linear phase filter.

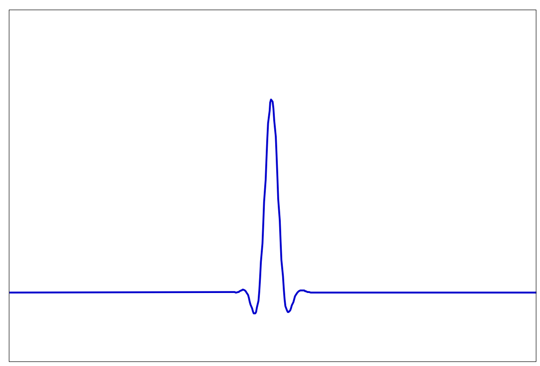
For linear phase response and time coherency. Fast roll off protects against aliasing distortion from high amplitude high frequency content. Best for recordings that are loud, compressed, and with lots of treble. Will contain substantial ringing before and after transients(pre-echo and post-echo). Note that the ringing occurs at the nyquist frequency (½ of the sample rate), so it is not directly audible. However, it can cause intermodulation distortion in downstream components.



Filter 1: Fast roll-off linear phase

Filter 2: Slow roll-off linear phase filter.

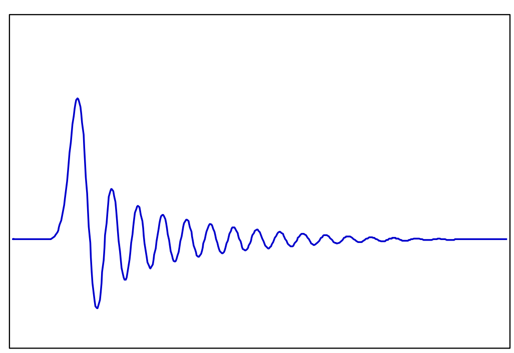
For linear phase response and time coherency. Best for acoustic music without compression and artificially high levels of treble. Will have very low levels of ringing before and after transients but is susceptible to distortion artifacts caused by high amplitude high frequency information in the program material.



Filter 2: Slow roll-off linear phase

Filter 3: Fast roll-off minimum phase filter.

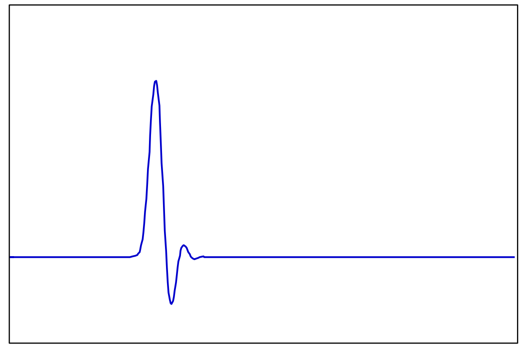
Not linear phase in the pass band. Fast roll off protects against aliasing distortion from high amplitude high frequency content. Best for recordings that are loud, compressed, and with lots of treble. Will contain substantial ringing caused by transients, but all of the ringing is shifted to after the transient, which can reduce the perceived effects off downstream intermodulation distortion due to the Haas Effect.



Filter 3: Fast roll-off minimum phase

Filter 4: Slow roll-off minimum phase filter.

Not linear phase in the pass band. Best for acoustic music without compression and artificially high levels of treble. Will have very low level of ringing caused by transients and ringing will be shifted to after the transient, which can reduce the perceived effects of downstream intermodulation distortion due to the Haas Effect.



Filter 4: Slow roll-off minimum phase

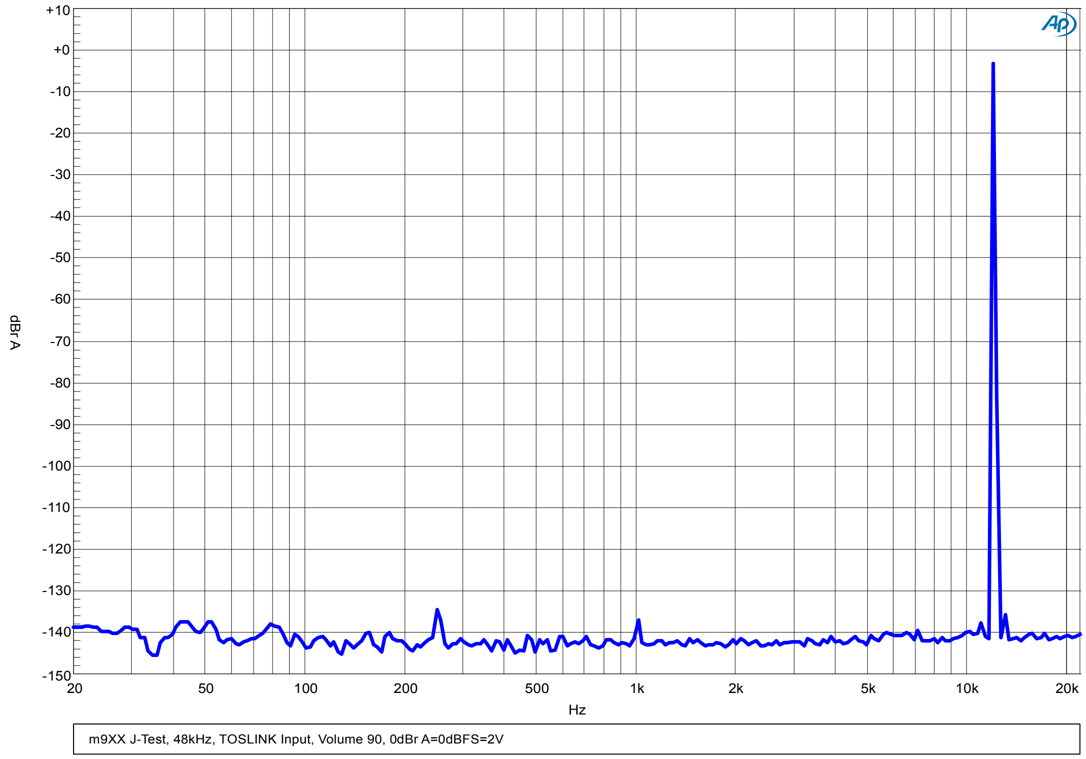
USB Interface

The USB streaming controller is implemented in a 500MHz, 8 core XMOS processor, XS1-U8A-64-FB96. The USB interface operates in asynchronous mode which means that the m900 is the clock master and the USB interface simply delivers data to buffers in the XMOS processor. The ultra low-noise master clock in the m900 is then used to to clock the audio data to the DAC. This system design is immune from USB buss jitter.

Sample rates from 44.1kHz to 384kHz are supported with 32 bit data as well as DSD64 (2.82MHz) and DSD128 (5.64MHz) via DoP DSD over PCM. "DoP" is a format that allows audio applications on a computer to transmit DSD files packed in to a standard PCM audio stream. DSD64 is packaged in to a 176.4kHz PCM stream and DSD128 is packed in to a 352.8kHz PCM stream. Special bits are added to the DSD stream that indicate to the m900 processor that the data DSD and not PCM so that it can configure the DAC to play DSD data.

TOSLINK Interface and PLL Clock

TOSLINK was chosen for its complete ground isolation from whatever system is connected to it. As well, DVD, BluRay, Apple TV and many other devices have TOSLINK outputs. The XMOS processor is responsible for receiving the TOSLINK data at up to 96kHz/24bit. The recovered clock from the TOSLINK stream is regenerated by an ultra low jitter (50ps) hybrid analog-digital PLL (Phase Locked Loop). The corner frequency of the PLL is 1Hz so there is over 90dB of jitter rejection at 1000Hz. The software based TOSLINK receiver in the m900 is immune from interface jitter unlike traditional hardware based digital audio receivers. Below is an FFT plot of the m900 output while playing the J-Test signal. The J-Test signal is designed to be the worst case data pattern for inducing jitter in receiver circuits. The only visible jitter induced side bands, which can be seen on either side of the 11.025kHz tone, are more than 130dB down from the fundamental and represent an rms jitter amplitude of 4.5ps.



Power supply

Ultimately, the audio quality of an amplifier and DAC is limited by the quality of their power supply. The power supply design in m900 brings bus powered headphone amplifier performance to an unprecedented level. The m900 has a dual input power supply allowing it to be powered solely from the USB bus, or from an external 2A USB charger.

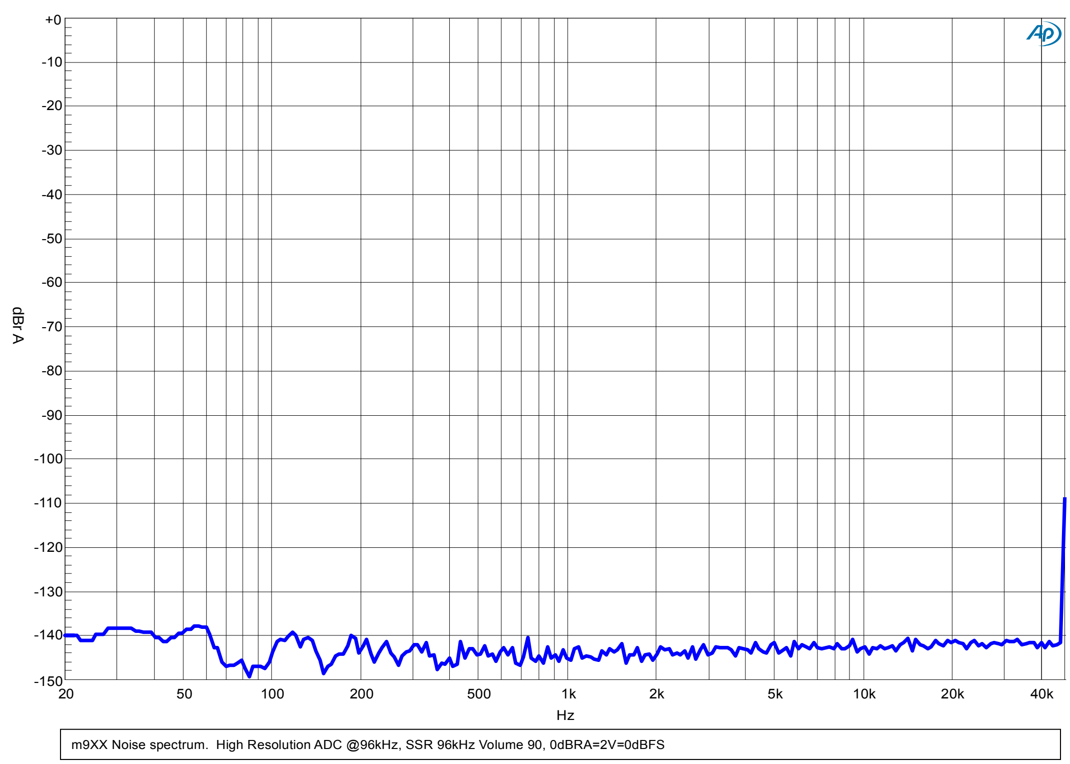
There are two Micro-B USB connectors on the rear panel, the first is a high speed USB 2.0 port with a maximum input current of 0.5A, and the second is for high power DC only (there is no USB data on this connector) and supports a maximum input current of 1.5A. The Micro B connectors were chosen for several reasons: they have a higher current rating than standard or mini B types, and their stainless steel construction is rated for 10,000 mating cycles, which ensures a long trouble free service life.

Any amplifier/DAC that runs off of bus power that is designed to provide improved performance over a computer sound card will require some sort of DC-DC converter circuitry. Converting the potentially noisy 5V bus power from a computer to the pristine bipolar power rails for high performance DAC and headphone amplifiers circuits was the first major design task for the m900. The result of this effort is a bus powered DAC/headphone amplifier with audio performance that rivals our flagship m920 reference headphone amplifier.

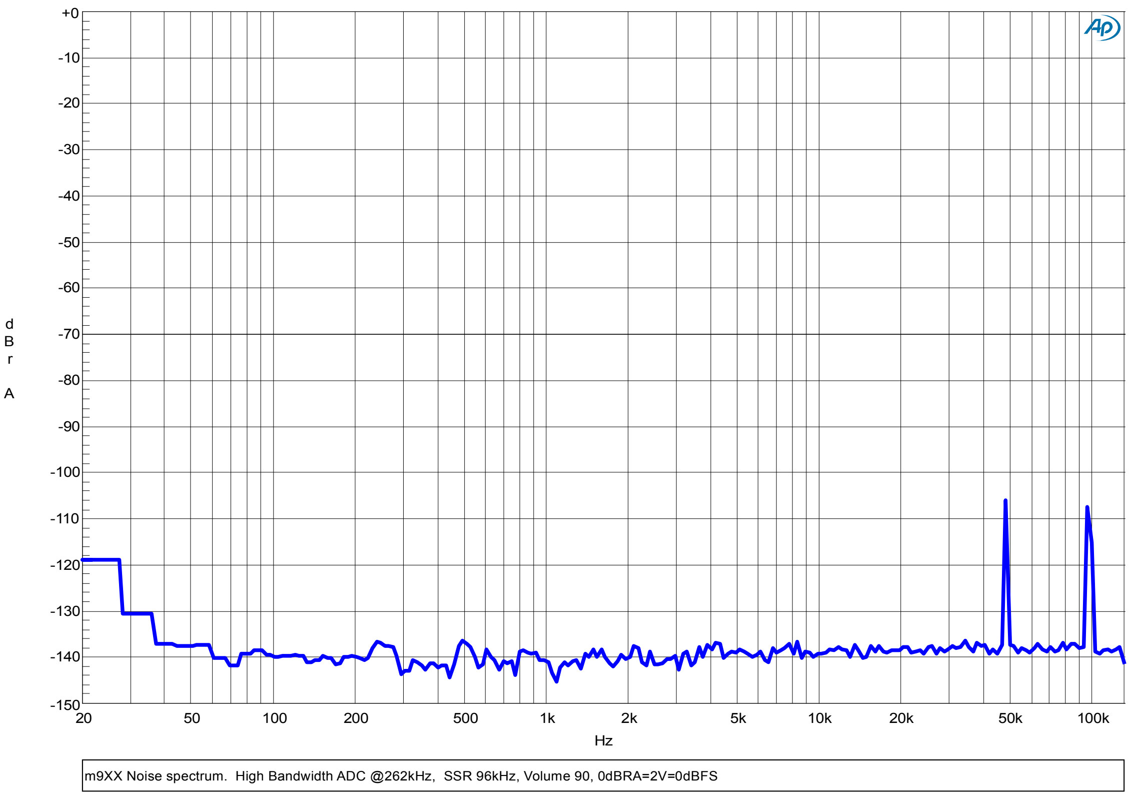
Noise from the computer USB port can cause jitter artifacts in the sensitive DAC circuits. To prevent this the m900 employes multi-tiered noise suppression. The first stage of noise suppression is provided by the high quality USB cables which are included with the m900. These high speed cables feature RFI filters that are built in as well as extra heavy 24AWG copper conductors for power and ground. The USB power is then filtered again right at the input connectors on the rear panel. From there, the power is separated in to individual supplies; one for the XMOS processor, one for the DAC, and one for the analog circuits. In all there are 5 separate power supplies in the m900.

The audio amplifier power supply rails are produced with an ultra low-noise push pull converter that runs synchronous to the digital audio clocks. This high-efficiency low-noise power supply circuit was originally designed for use in our portable microphone preamplifiers, which have an EIN (equivalent input noise) of -130dB. For the m900 we developed a new custom high current transformer for this power supply. Not only is this transformer capable of efficiently delivering high power, but it is also very well shielded to prevent radiated noise. This attention to noise suppression and isolation between digital and analog power yields a system with output noise of -109dBV A weighted and -106dBV 22-22kHz. Dynamic range is 115dB A weighted and 112dB 22-22kHz.

Below are two FFT plots of the noise floor of the m900. Both are made with the m900 on TOSLINK input at 96kHz with the volume set to 0. This first is made with the Hi Resolution ADC in the Audio Precision 2700. The sample rate of this ADC is limited to 96kHz so this plot goes up to 48kHz. Note the lack of any power supply or 60Hz AC powerline artifacts in the audio band. Just visible at the very right edge of the plot is the DC-DC converter noise which is 48kHz and synchronous to the input sample rate.



The second plot is using the High Bandwidth ADC in the Audio Precision 2700. The sample rate of this ADC is set at 262kHz so the plot goes up to 131kHz. Here the DC-DC converter fundamental and 2nd harmonic are clearly visible at 48kHz and 96kHz. Note that the level is well below -100dB below full scale.



The efficiency of the audio power supply allows the m900 to operate with +/-9V DC power rails when running on USB buss power, which results in available continuous power for the headphones exceeding 160mW per channel with both channels driven in to 32Ω headphones. One channel power in to 32Ω phones is more than 500mW.

The m900 automatically senses when the external 2A USB charger is connected to the high power DC input. Once detected, the m900 increases the DC power rails to +/-14.5V, which results in available continuous power for the headphones exceeding 1000mW per channel with both channels driven in to 32Ω headphones. One channel peak power in to 20Ω phones is more than 1600mW.

Sophisticated protection circuits monitor the power entering the m900 at all times and immediately shut off the power supply in the event of an over current fault condition. This protects the output amplifier from damage as well as ensuring that a fault condition does not create an over current problem on the computer's USB port.

Input and Output ESD, RFI, EMI Protection

Care has been taken to make sure that the input and output connectors are fully protected from ESD (Electro

Static Discharge). Voltages of 2500V or more are regularly encountered with ESD events on headphone cables, which can degrade the amplifier performance or even damage the device. Protecting from RFI (radio frequency interference) and EMI (electro-magnetic interference) is another important area of circuit design. With the prevalence of cell phones, Wi-Fi networks, Bluetooth radios, etc. care must be taken to avoid audio degradation.

Enclosure

The chassis enclosure of the m900 not only looks cool and feels great under your hand, but it is fabricated from extruded and sheet aluminum. We avoid the use of steel as it is magnetic and can react with fields from audio circuits. Also, aluminum is more permeable at radio frequencies, so it is a better material for protecting the m900 circuitry from external interference. The chassis, custom volume knob and headphone jacks are all finished with anodize which is extremely durable.

Reliability

At Grace Design we consider reliability to be equally important as performance. In fact, reliability *is* performance. Designing for reliability is a process that is integral to product development and has been refined over many years of designing and building products which get used in a variety of environments.

From broadcast facilities, concert halls, recording studios and living rooms to the jungles of South America, our products are among the most dependable available. This is evidenced by our warranty terms: the m900 is covered under a 5 year transferable warranty.

Thanks for reading.