White paper – Continuous-Sigma™ (C∑)

Introduction

Indice Semiconductor has developed Continuous-Sigma, a new design methodology that challenges long held beliefs and conservative design paradigms through leading performance, size, cost and power consumption. Just as Delta modulation was superseded by Delta-Sigma (Δ∑) converters, Continuous-Sigma is the next evolutionary step, removing costly and power hungry sections whilst increasing performance. Already available in a High Resolution Audio (HRA), cost effective, professional grade performance power amplifier, Continuous-Sigma is set to open new product in signal conversion applications.

Continuous-Sigma™ (C∑)

In signal conversion, Delta-Sigma and Successive Approximation Register (SAR) ADCs currently represent a large portion of the world's analog to digital converters. Delta-Sigma data converters provide excellent resolution at modest speeds (16-32 bit at 96KHz typical), but at considerable relative cost. Conversely SAR achieves great speed at low cost, but with only limited resolution (~14bit at MHz frequencies). Unfortunately, SAR's cannot achieve higher resolution capable of bridging the gap due to architectural limitations, while cost and other limitations in Delta-Sigma converters prevent it from competing with SAR, even at low resolution.

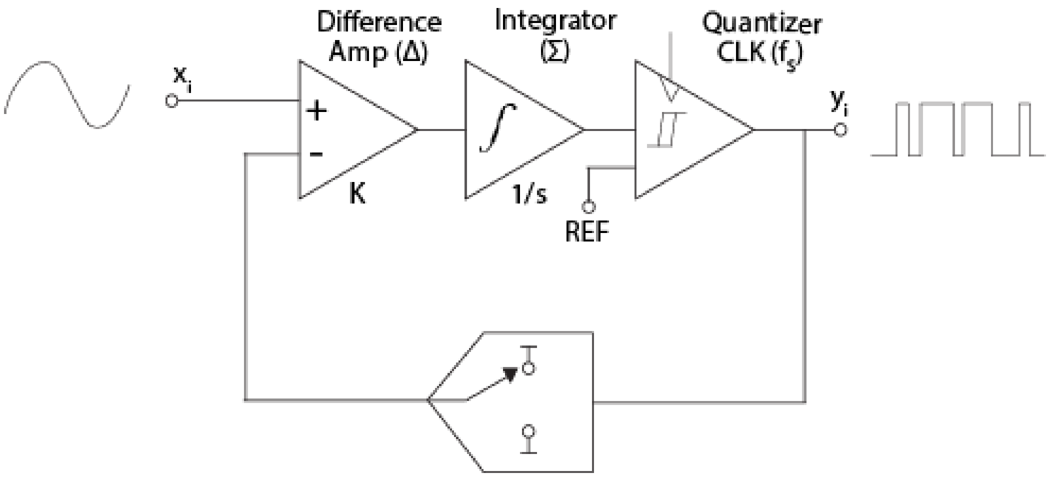

Figure 1: Delta-Sigma value to time domain converter.[1]

Continuous-Sigma represents an evolutionary leap in data converter architecture. As opposed to the clock-based Delta-Sigma converter, Continuous Sigma is completely asynchronous; it does not suffer from timing and switching artifacts (the details of which are explored below). Nor does Continuous-Sigma depend, as with SAR, on a high accuracy DAC, so its linearity is not as limited in that way. Continuous-Sigma has lower complexity and

[1] Baker (2011.) Texas instruments SLYT423

power draw than Delta-Sigma converters, but at a cost lower than SAR converters[2] while simultaneously delivering more precision and performance than either.

The Continuous-Sigma architecture illustrated in Figure 2 is fundamentally a value to time domain converter. The output is a series of time-varying pulses that give a digital representation of the analog input. This pulse train is easily and quickly converted to binary values in a similar fashion to Delta-Sigma converters. In contrast SAR converts directly to multi-bit binary.

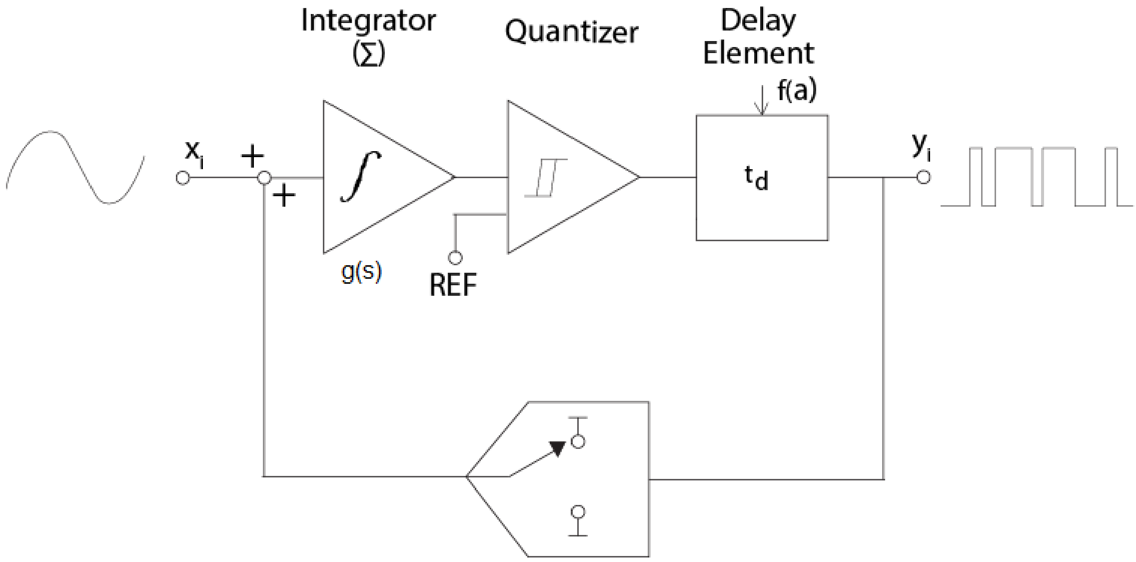

Figure 2: Continuous-Sigma value to time domain converter.

As with Delta-Sigma converters, an integrator accumulates feedback and input signal, but comparing Figure 1 with Figure 2 reveals some important differences. Firstly, the error difference mechanism in Delta-Sigma converters is replaced with a simple summing node in Continuous-Sigma, removing any transition errors not part of the output. Secondly, the integrator function in Continuous-Sigma is not the traditional form used in Delta-Sigma conversion, reducing non-ideal behavior[3]. Lastly, where the Delta-Sigma converter uses a clocked comparator, Continuous-Sigma implements a controlled delay element that is *asynchronous*- **not clocked.** This last difference is perhaps the most profound. Being able to increase the Over-Sample ratio (OSR) without the traditional issues limiting Delta-Sigma sample Frequency (Fs) is key to the advantages presented.

[2] Closer to a dual-slope converter in cost

[3] Norsworthy, Schreier & Temes Delta-Sigma Data Converters (1997: p13, 20)

Advantages of Continuous-Sigma over Delta-Sigma conversion

Vastly improved group delay

A typical audio grade Delta-Sigma ADC or DAC may have a group delay in the order of one millisecond. The delay is inherent in the system design, but may be unacceptable in professional recording and playback systems. The same delay limits the frequency response of closed loop systems, such as noise cancelling headphones, where countering the original waveform requires incoming wave forms to be encoded, processed, and then converted back to electrical current and then finally acoustic energy. Delay limits the upper frequency the system can accurately cancel. If Continuous-Sigma with performance shown in Figure 3 were to be used in the same setting, the group delay can be reduced by a factor of 15 or more. This enables, for instance, noise cancellation in the kHz range which is a challenge today. Putting this in perspective, 1ms delay is the equivalent to having 1ms of stored information, which must be paid for both at a silicon level and solution level.

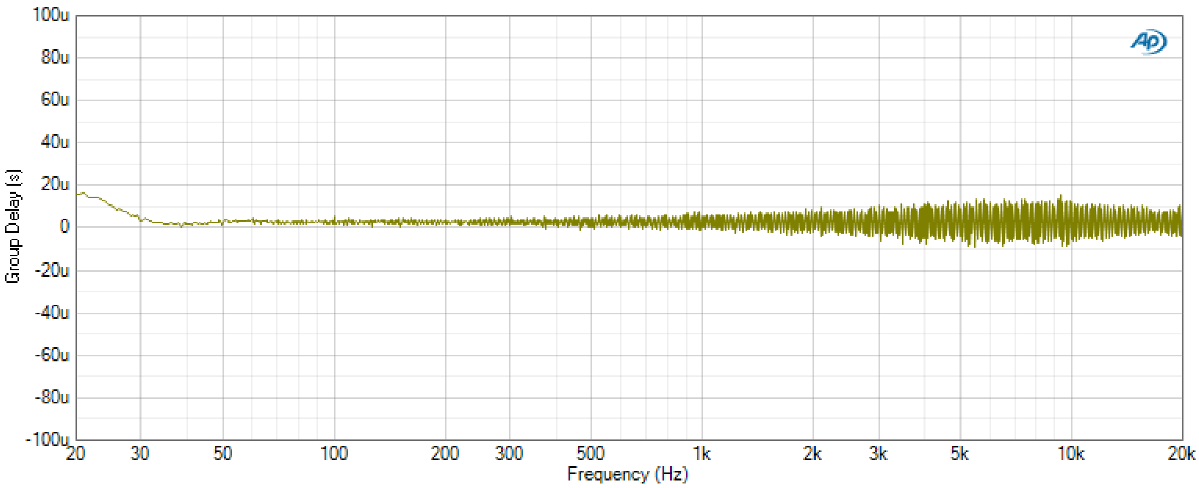

Figure 3: First order Continuous-Sigma exhibiting virtually zero group delay[4].

In the example of Figure 3, Indice's Blade amplifier[5] was measured from input to the load-outside the filter, therefore including the filter delay. The results are similar when testing an ADC using a decimation filter. Analogous to an LC filter, decimation filters add additional group delay due to the time lag in converting 1 bit, time to digital output at high frequency to the multi-bit output at a low frequency.

Low noise floor for minimal order

Similar to Delta-Sigma systems in shape, the noise floor of Continuous-Sigma is dictated mainly by OSR (typically sampling clock carrier to passband ratio) and the number of orders, shown in Figure 4. As stated earlier, Continuous-Sigma is not limited to the same oversample ratio as Delta-Sigma converters, as the carrier is free to operate at frequencies decades higher than in an equivalent Delta-Sigma system. Indice has demonstrated that a single order Continuous-Sigma system has equal or better noise floor performance for a given

[4] The reader will notice that some parts of the measurement appear to have 'negative' group delay. This is measurement error is due to the AP515 limitations, the system group delay is indeed stable and positive.

[5] Refer to the indicesemi.com for Blade datasheets and specifications.

passband over a Delta-Sigma converter with three or more orders, by increasing the maximum switching frequency by one decade. Going to a second order with Continuous-Sigma has the same relative gain as with Delta-Sigma. This is very important, not just from a simplicity and cost perspective, but also with regard to stability. Whereas a second order Continuous-Sigma has superior performance and is guaranteed to be stable, it is impossible to guarantee stability with three or more orders necessary to achieve similar results with Delta-Sigma conversion[6], with lower performance. Additionally, the increased time precision allows Continuous-Sigma to achieve high precision without the need of a multi-bit DAC, guaranteeing linearity.

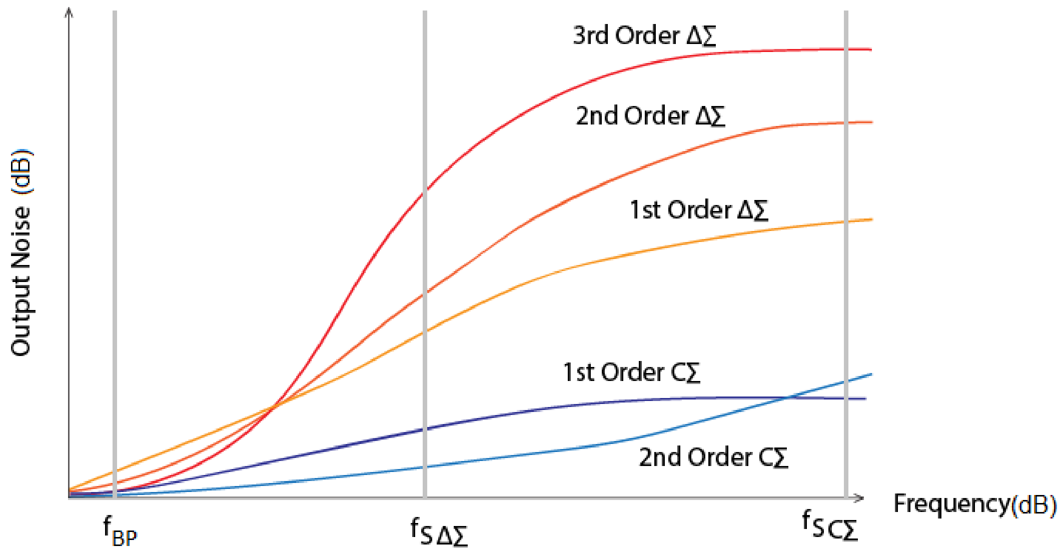

Figure 4: Relative noise floor shapes[7]

Broader passband

In both Delta-Sigma and Continuous-Sigma systems, the passband limit is a function of the desired noise energy level, frequency range, OSR and number of orders of the system. Higher OSR means that the passband - or the bandwidth of the signal to be encoded, decoded or amplified - will have either a lower noise floor for a given bandwidth, or greater bandwidth for a given noise floor and number of orders.

Another advantage of Continuous-Sigma input scheme over Delta-Sigma modulation, particularly in analog input systems such as ADC and amplifiers, is the way the feedback interacts with the input signal. The result is that the input is able to modulate all the way to the analogue voltage rail without clipping. Traditional Delta-Sigma converters are limited to half the rail due to the delta section; this alone is a 6dB advantage.

[6] Norsworthy, Schreier & Temes Delta-Sigma Data Converters (1997: p141)
[7] Baker (2011) Texas instruments SLYT423

D-class amplifiers

Traditionally, D-class amplifiers have been considered to be of poor quality, particularly when compared with A-class amplifiers. Whilst the past performance of D-class amplifiers warrants distain from the audiophile community, it is unfair to blame the D-class as a category. D-class only refers to a half or full bridge output stage topology. The only real difference between it and A or AB-class amplifiers is that the switches operate in saturation mode only, whilst A or AB-class switches operate in the linear region. Topologically, there is little other difference; so why has D-class sounded so much worse traditionally?

The answer to this is that ideal operation of half or full bridge systems is essentially impossible. Ideal operation of half or full bridge systems in saturation mode requires infinitely low output impedance, and infinitely fast transition speeds which are perfectly linear and symmetrical from one transition to the next. These are impossible: with every transition, error and noise is introduced, due to aspects such as dead time, shoot through, over shoot, and variations in output impedance. This means that the faster a D-class amplifier switches, the greater the accumulation of error. Worse still, if the carrier frequency is constant, then harmonics develop, which then modulate with the pass band, taking performance from bad to worse.

Since the early days of D-class, the efforts of designers to reduce or mitigate these issues have met with varied success. Some tried introducing feedback from various places, others preferred brute force and allowed limited shoot through of the bridge. Indice's Continuous-Sigma has taken previous achievements in this area to a new level. The Blade range has been tested by industry, with many third parties observing that Continuous-Sigma equals or even supersedes the best of A-class amplifiers - but of course at a mere fraction the size due to the huge jump in efficiency (>96%) over traditional analog amplifiers.

This jump in performance is made possible due to our real-time error feedback system which compensates for switching error, cross-over distortion, and power supply ripple all at once. As mentioned, Continuous-Sigma does not have a clock to synchronize the output as with other systems, but is asynchronous. One advantage of this asynchronous operation is with Electro-Magnetic Compliance (EMC). Frequency smearing greatly reduces issues faced by fixed, synchronous carriers as both fundamental and higher order harmonics experience 'smearing'.

Not being fixed, the carrier frequency varies depending on the input signal, which means that any intermodulation artefacts, while still present, are well below the noise floor in the pass band.

Figure 4 is an attempt to compare noise shaping of Delta-Sigma with Continuous-Sigma conversion. Continuous-Sigma's asynchonicity implies that it technically has no sample frequency (Fs). Instead, it has an upper switching frequency determined by the minimum quantizer delay td(min). Therefore:

$$Fmax = \frac{1}{4 * td(min)}$$

Switching frequency is modulated by the input signal and feedback interacting at the integrator, with maximum frequency at zero input. Frequency decreases as the input signal magnitude increases, as per figure 5 below:

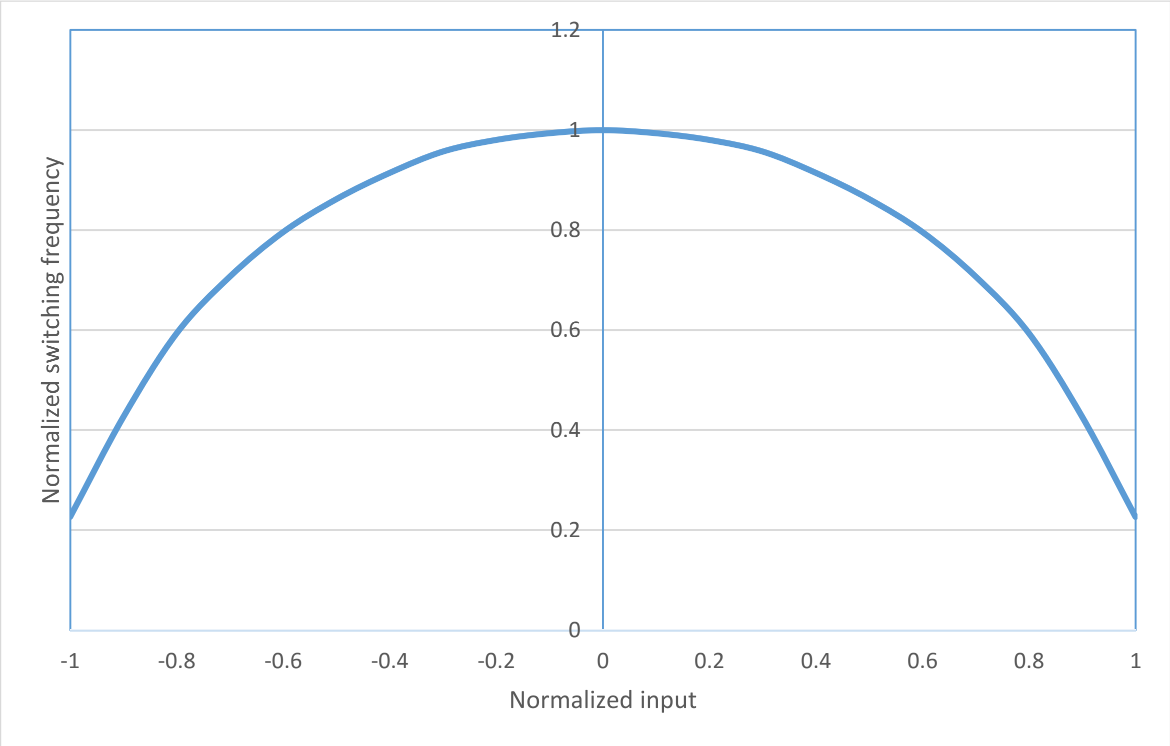

Figure 5: Switching frequency vs input signal

Filter design

In traditional D-class controllers, having a filter external to the feedback path would mean poor damping control, with the system limited by the performance of a bulky, expensive demodulation stage. As a result, many main feedback paths tend to come from the filter output - the same electrical 'net' as the speakers. This means that vital carrier information, in the form of ripple, must be present at the speaker for those systems dependent upon it.

There are many issues with this. Firstly, the switching frequency, and carrier amplitude at the speaker wires is restricted by EMI requirements. This immediately limits the system upper switching frequency, which in turn limits oversampling rate, noise shaping and passband. Secondly, the very minimal carrier ripple allowed at the output and therefore feedback path, is at the mercy of the load. This is even before considering the two imaginary poles introduced into the feedback path. Such a design may have multiple potential solutions **with an ideal load;** one solution is desirable, many are not. Adding an unknown load to such a system makes guaranteed stability improbable. A speaker load is far from ideal; they are nonlinear, time variant, electromechanical systems, all of which makes stability of such feedback schemes very difficult, especially over normal manufacturing and environmental tolerances[8].

In practice, most commercial D-class amplifiers have relatively low carrier switching frequency; typically, in the order of 400KHz. Such an amplifier, to meet EMI, would need an output filter roll off frequency below 40KHz, or one decades away. This immediately precludes HRA from such amplifiers. Physically, this introduces the issue of size and cost of such a low frequency filter.

Other solutions may offer higher speeds similar to Continuous-Sigma, but this can come at the cost of reduced quality. As previously explained, Delta-Sigma systems have clocked or gated quantizers, with frequencies set deliberately to keep switching speeds low enough as not to allow excessive accumulation of transition related error due to the non-ideal behavior of the 'delta' section[9]. Whereas real amplifiers will always have a slew and bandwidth limits, Continuous-Sigma is immune by virtue of having no equivalent 'delta' limitations.

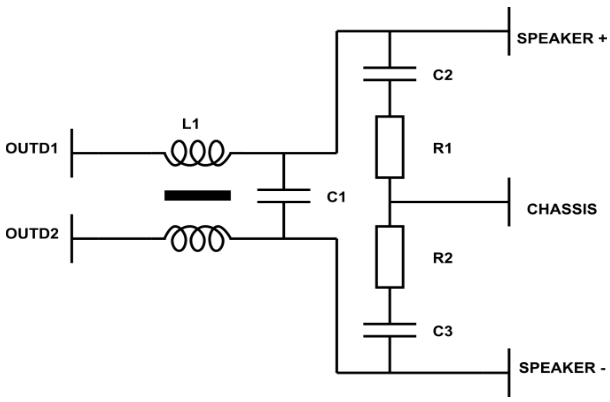

Figure 6: Simple, damped output filter[10]

This allows Continuous-Sigma a much higher equivalent switching frequency, typically 1MHz or more. By its nature, the Continuous-Sigma D-class controller has a simple and elegant architecture allowing much greater oversample ratios. With only a single pole in the critical feedback path, stability is inherent by design. The only imaginary pole pair is in the external filter, which is easily damped with suitable RC snubbers required in any switch mode amplifier for EMC, such as in Figure 6 above. Because the carrier is now more than double other systems, so too can the filter roll off be, exceeding 50KHz, HRA ready.

It is true that without the feedback paths outside the filter non-linear and other undesirable filter artefacts are now uncompensated. Readily available, off the shelf components can be selected with such undesirables only affect frequency well out of the pass-band. Also, inductor DCR can be drastically reduced simply by using very low inductance value, but higher current rating. This allows the designer to 'dial in' competitive damping factors by selecting an output impedance for a desired load range. In fact, by controlling the damping factor with external components, the product engineer can tailor the system to meet any

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[8] Jackobsson & Larkson, Modelling and compensation of non-linear loudspeaker (2010 : p 10 fig 3.1)

[9] Norsworthy, Schreier & Temes Delta-Sigma Data Converters (1997: p210, 341, 13,)

[10] L1 need not be mutual inductors, separate inductors achieve similar results, consuming more volume.

desired damping factor - low for broad sound stage, or high for narrow, all with the same chipset.

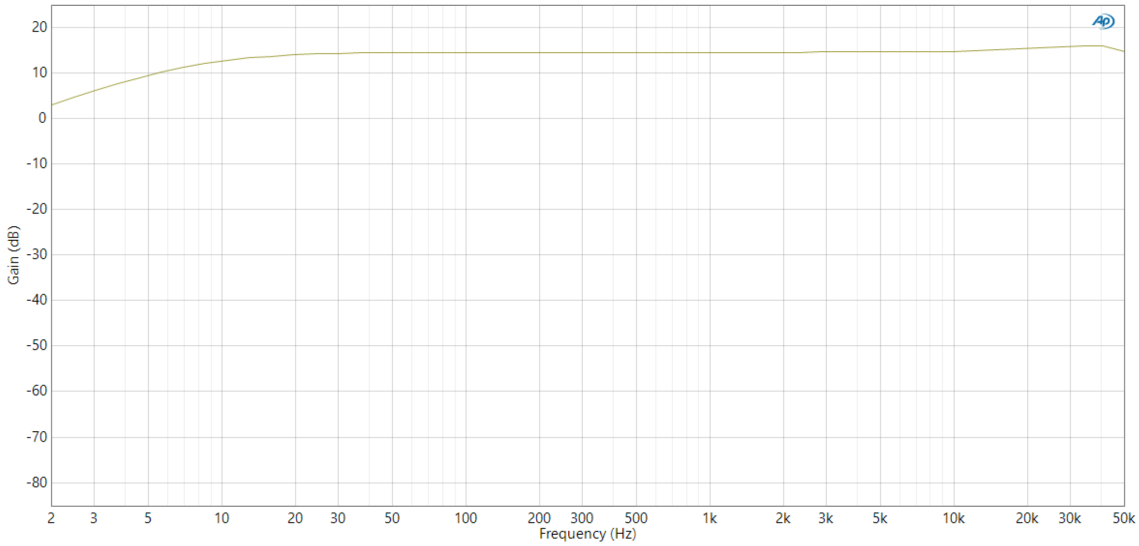

Figure 7: Flat gain response over the largest Passband of any D-class amplifier known due to Continuous-Sigma.

A welcome side effect of such a simple control loop, Indice's Continuous-Sigma, D-class controller has incredibly flat gain response from DC to well over 50KHz. This again makes it HRA ready, a feature only available with ultra-high switching speeds, shown above in Figure 7. Note that the high pass filter connected in this instance was set to 10Hz, Continuous-Sigma operates from DC up to the required upper frequency for a given application.

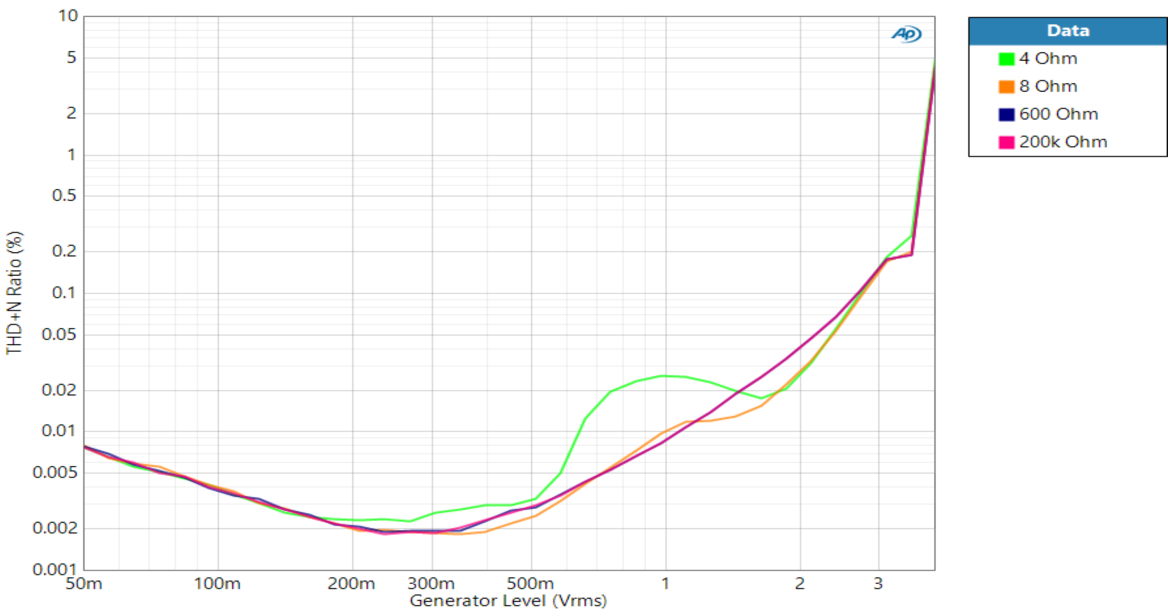

Figure 8: THD+N for 4Ω, 600Ω and 200KΩ load

Figure 8 above illustrates an amplifier controlled by Continuous-Sigma driving 4Ω, 8Ω, 600Ω and 200KΩ loads, with exactly the same output filter and feedback configuration, optimized for an 8 ohm load. Not only is the performance relatively consistent, but the higher the load impedance the better performance becomes. Other D-class controllers exhibit the opposite behavior. Despite not being optimized for 4 ohm, high performance is still achieved. Had the filter been optimized for 4ohm, the curve would match the higher impedances more closely, the only cost being slightly larger inductors.

Using this, the designer can now construct an amplifier with consistent performance over a range of loads, greatly expanding the end product versatility. One example: an automotive amplifier may be optimized for 1Ω, 2Ω, 4Ω or 8Ω speakers without any special considerations or concerns over stability or damping.

One final important figure of merit is an amplifier's stability of THD+N performance over frequency range. Industry standard implies this measurement be performed at 1KHz. Naturally, this is subject to 'opportunism'. A given amplifier may have its parameters optimized for this frequency alone, at the expense of performance at others. Another sleight of hand limiting choice of load, where performance at 4Ω for example is vastly better than at 8Ω. Figure 9 shows that Continuous-Sigma does not make such compromises, whether the frequency is 10, 100, 1K, or 10KHz, or if the load varies.

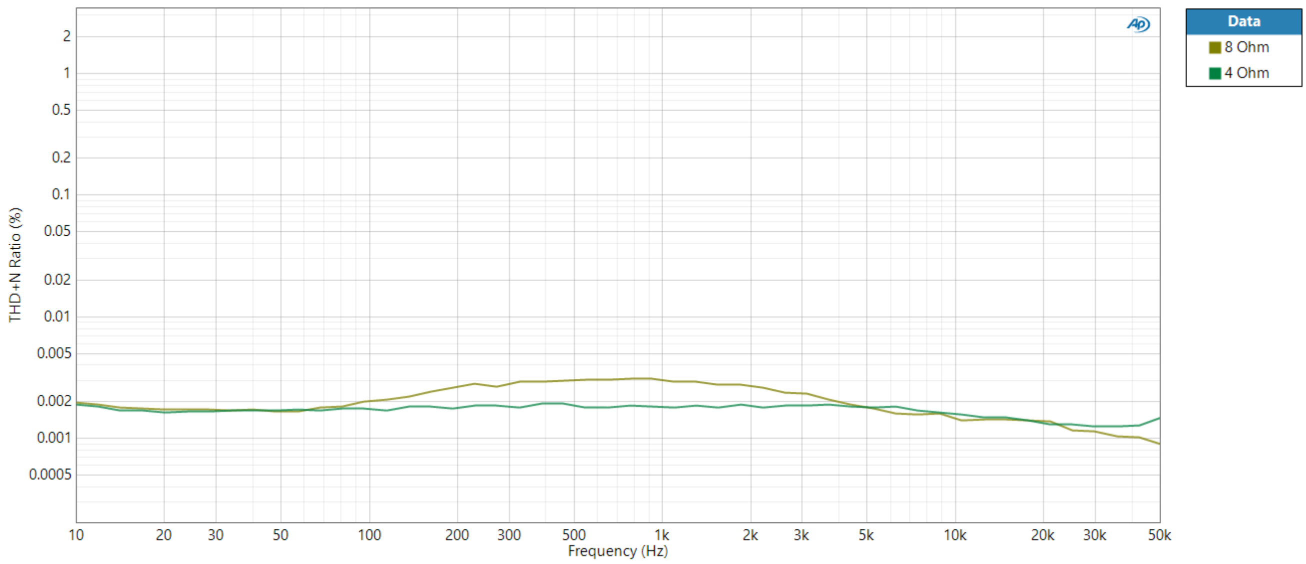

Figure 9: Stable THD+N over pass band

While new to the audio field, Continuous-Sigma is already proving itself against industry standards. Continuous-Sigma very simple design makes it easy to implement, while enhanced performance and efficiency make it ideal for the next generation of energy sensitive products.

Continuous-Sigma betters both A-class performance, and D-class cost.