

## New Technology Increases the Dynamic Ranges of Data Acquisition Systems Based on 24-bit Technology

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The linear operating range of high-quality measurement accelerometers and microphones has for many years been significantly better than that of the analog signal conditioning electronics and analog-to-digital converters (ADCs) of data acquisition systems. This is despite the fact that data acquisition systems today are typically based on 24-bit ADCs, and theoretically able to handle signal dynamics of up to 146 dB. In practice however, most of these systems do not have a useful dynamic range higher than 100-110 dB. Consequently, system operators must be very careful in optimizing the signal chain dynamics in order to avoid overload and underrange situations. This article describes the high dynamic ranges that can be achieved using today's state-of-the-art designs.

**Dynamic Range and Frequency Range.** The ratio between the highest and lowest signal a system can handle is defined as its dynamic range. If the dynamic range is too low, high signals will typically be clipped and distorted while the low signals will typically be buried in system noise originating from the transducer element and the electronics conditioning the transducer. In technical terms, the dynamic range (DR) is the ratio between the rms value of a full-scale sine wave  $V_{FS}$  and the rms value of the system base noise  $V_N$ . It is typically given in dB –

$$DR = 20 \times \log \frac{V_{FS}}{V_N} \quad (1)$$

When discussing dynamic range, the frequency range of the measurement must be taken into consideration. In a well-designed system, the inherent system noise can be characterized as white noise. Consequently, if all elements of the measurement chain are linear in nature, the dynamic range of the measurement can be improved by reducing the measurement frequency range. This is actually one of the advantages of the commonly used FFT analysis. For the above statement to be valid, it is essential that no artifacts are introduced in either the time or the frequency domains when performing narrowband analysis.

**Dynamic Range of Transducers.** For the last 30 to 40 years, sound and vibration transducers have outperformed the

subsequent analysis systems in linearity and dynamic performance. A high-quality transducer, including preamplifier, can deliver a practically noise-, spurious- and distortion-free signal over a dynamic range of 120-130 dB using broadband, and 160 dB using narrowband, analysis. In a well-designed transducer, the limiting factors for achieving a high dynamic range are mainly the noise floor  $V_N$  and the clipping level of the electronics (preamplifier). The transducer element itself does not limit the performance.

The noise floor  $V_N$  of a high-quality preamplifier has for the last 30 to 40 years been in the region of 3-15  $\mu$ V in the audible frequency range. The maximum linear output of a DeltaTron®/ICP® transducer is 5  $V_{rms}$  (7.071  $V_{peak}$ ). Table 1 provides examples of dynamic ranges that can be expected for a high-quality transducer.

Throughout this article, a bandwidth of 25.6 kHz is used for broadband comparisons. For narrowband comparisons, 6 Hz and 1 Hz are used. 6 Hz corresponds to the effective noise bandwidth of a 25.6 kHz FFT analysis with 6400 lines using Hanning weighting.<sup>1</sup>

Assume that a transducer can be used for narrowband measurements over a range of 160 dB (effective noise bandwidth of 6 Hz), given that no other factors affect the measurement chain. In other words, a high-quality transducer can be expected to deliver a linear signal over 160 dB when applying narrowband analysis.

**Analysis Chain Imperfections.** The whole analysis chain should ideally match a high-quality transducer's performance. As this has not been the case so far, every analysis system has included an input attenuator to allow the user to range the performance of his analysis system to the output signal of the transducer.

The useful dynamic range of the analysis system is not only determined by the clipping level and the noise floor. The list below includes some of the other factors that limit the analysis system performance.

- Harmonic Distortion – signals caused by nonlinearities in the analog signal conditioning, typically characterized as a family of harmonic components leveled relative to the measurement signal.
- Cross-talk – signals caused by inter-channel coupling, leveled relative to the signal level of the originating channel.

- Spurious – signals caused by various phenomena such as power supply imperfections, clock circuits, bus communication and EMC coupling between circuits. Spurious signals are difficult to control when designing for a high dynamic range.
- ADC Resolution – an ADC has a final quantization, which today is typically between 16 and 24 bits.
- ADC Nonlinearity – digital distortion components caused by uneven quantization step sizes in the ADC and the on-chip DSP.
- Aliasing – signal artifacts originating from signal components of frequencies higher than the Nyquist frequency, typically leveled relative to the measurement signal.
- DSP Imperfections – modern analysis systems perform filtering, decimation and the actual analysis in the digital domain.

Throughout the whole digital analysis chain, a high dynamic range requires high-speed calculations of high accuracy. High-speed DSPs are both expensive and have high power consumption. Careful algorithm design can provide a very high dynamic range for the whole chain.

**System Considerations.** No system is better than its weakest link. The analysis chain consists of coupled elements, each with a limited dynamic range as illustrated in Figure 1.

The ADC has been the weakest link in the analysis chain ever since the invention of digital signal processing. New ADC designs have, however, improved performance dramatically. Table 2 gives a rough overview of the historical evolution in ADC specifications. Traditional ADC designs still lack performance when compared to the transducer (see Table 1).

**Overcoming the Analysis Chain Imperfections.** The fact that the transducer has historically always outperformed the analysis chain with respect to dynamic range has been compensated by the inclusion of an input attenuator in the analysis chain. This has, in practice, compensated for the limited dynamic range of the ADC and also limitations in the following DSP chain. The disadvantage is a high risk of bad measurements as overload and underrange situations can occur (Figure 2). An overloaded measurement is erroneous and has to be re-measured. There is no way of estimating the correct result.

Overloads are probably the biggest cause of bad measurement results. For

Table 1. Dynamic ranges for a high-quality transducer.

Bandwidth, Hz	25.6 k	1 k	24	6	1
$V_{FS}, V_{RMS}$	5	5	5	5	5
$V_N, V_{RMS}$	3 $\mu$	600 n	93 n	47 n	19 n
DR, dB	124	138	154	160	168

Table 2. A historic overview of specifications of ADCs for sound and vibration analysis. Sampling frequency  $F_s$ .

Year	ADC Res, bits	Dynamic Range (DC – $F_s/2$ ), dB
1970	10-12	60
1980	14-16	70
1990	16	80
2000	24	100
2005	24	110

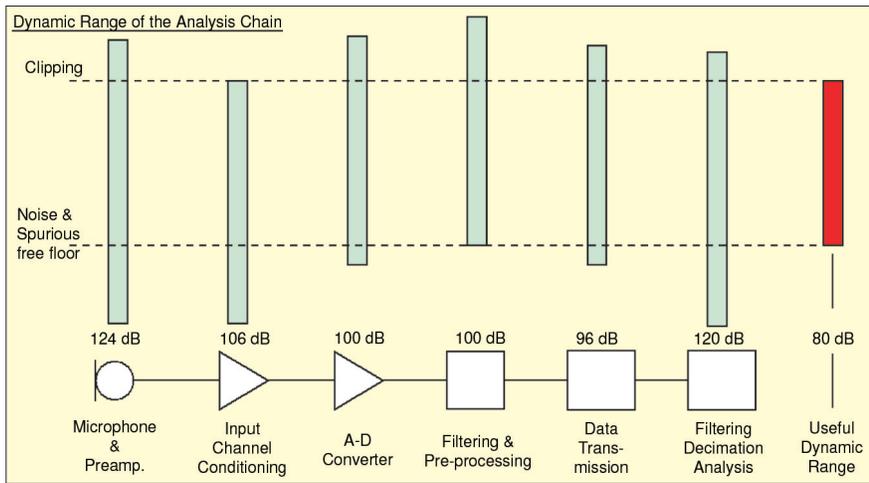


Figure 1. Example of dynamic ranges of an analysis chain

multichannel measurements, it is becoming an even bigger issue as it is getting more and more difficult to overview the whole measurement scenario and avoid defective measurements. Furthermore, product optimization requires testing in higher dynamic ranges for many applications.

**Potential Dynamic Range of a 24-bit System.** How far can a system based on 24-bit quantization be taken? The following section considers potential system performance if 24-bit quantization is taken to the theoretical limit. An approach similar to the one applied to the transducer can be applied to the system with respect to broadband and narrowband analysis. Careful system design can ensure that the quantization noise is, theoretically, random and thus with a uniform spectral density (white). The theoretical dynamic range in dB can be calculated as:<sup>2</sup>

$$DR = 20 \times \log \left( 2^N \times \sqrt{\frac{F_s}{2 \times F_{NBW}}} \times \sqrt{1.5} \right) \quad (2)$$

where  $N$  is the system quantization in bits,  $F_s$  the sampling frequency and  $F_{NBW}$  the effective analysis bandwidth in Hz. Table 3 shows the dynamic range in different bandwidths as a function of system quantization.

The theoretical increase in dynamic range can be expressed as a ratio between the sampling frequency  $F_s$  and the width of the narrowband analysis  $F_{NBW}$ :<sup>2</sup>

$$\Delta DR = 20 \times \log \sqrt{\frac{F_s}{2 \times F_{NBW}}} \quad (3)$$

Narrowband analysis can improve the analysis depth quite dramatically and an ideal 24-bit system can fully match the performance of modern transducers (see Table 4).

**New Technology Introduction.** The

above shows that if ADC performance can be improved by 20 to 30 dB in combination with a careful design of the whole analysis chain, then problematic input ranging can be eliminated. Brüel & Kjør has, over the years, looked into this and has recently introduced a new technology designed to increase the useful dynamic range of the whole analysis chain sufficiently to eliminate the use of input attenuators. Ease of performing sound and vibration measurements is thus dramatically increased.

**Dyn-X Technology.** This new technology is called Dyn-X. In brief, the technology utilizes a specialized analog input design to provide a very high dynamic range of the analog circuit pre-conditioning the transducer signal before forwarding it to the ADC as shown in Figure 3. The digitizing is performed synchronously in two specially selected, high-quality, 24-bit ADCs. Both data streams are forwarded to the DSP environment where dedicated algorithms in real-time merge the signals while obtaining an extreme high-accuracy match in gain, offset and phase. An important requirement of the design process was that no technical drawbacks should be introduced in either the time or frequency domain with respect to distortion and other artifacts, when compared to existing designs.

The results are very positive and have allowed for a complete redesign of the input channel from the transducer to the analysis result. Figure 4 compares the dynamic range of a standard 24-bit input channel with the new Dyn-X input channel.

Note that the dynamic range is shown in a 24 Hz bandwidth corresponding to what will be achieved with a 25.6 kHz FFT with 6400 lines and Hanning weighting. It can be seen that the Dyn-X input

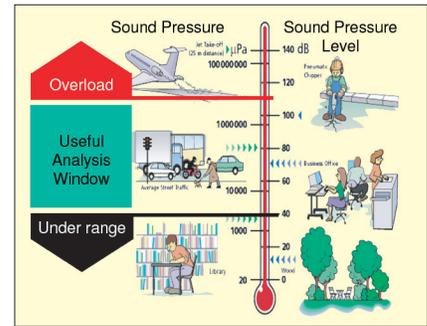


Figure 2. The effect of using an input attenuator.

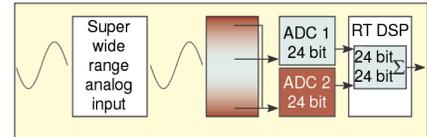


Figure 3. A simplified block diagram of the Dyn-X technology.

channel covers the same range as the 7 input steps of a standard 24-bit input channel.

**Dyn-X Technology System Performance.** It has previously been mentioned that the whole analysis chain must provide a 25.6 kHz broadband dynamic range better than 124 dB, and correspondingly better than 160 dB in a 6 Hz narrow frequency band, in order to match the specifications of high-quality transducers. The following examples compare the performance of the Dyn-X input channel to a standard 24-bit input channel. Note that, when set to a lower input range, a standard channel can, in theory, provide measurements of similar quality, but with a high risk of generating overloads. The maximum input is  $7 V_{rms}$  ( $10 V_{peak}$ ) for the Dyn-X input channel and  $5 V_{rms}$  ( $7 V_{peak}$ ) for the standard 24-bit input channel.

In Figure 5 (left) the Dyn-X input channel is compared to the 24-bit standard input channel for a 1 kHz sine wave attenuated 60 dB corresponding to a signal level of  $7 mV_{rms}$ . FFT analysis in 25.6 kHz, 6400 lines and Hanning weighting was used resulting in an effective noise bandwidth of 6 Hz.

For the Dyn-X, input channel noise and spurious components are below  $-160$  dB, thus matching the dynamic range of high-quality transducers. The noise floor of a standard 24-bit input channel is approximately 30 dB higher and ADC non-linearity is seen by the presence of spurious components.

In Figure 5 (right), a similar comparison is performed, but now with the sine wave attenuated 150 dB corresponding to a signal level of  $0.22 \mu V_{rms}$ . The noise floor and the spurious components are

Table 3. Dynamic ranges for different system quantization and bandwidth.  $F_s = 65,536$  Hz.

N, bits	Resolution	Dynamic Range, Bandwidth, Hz				
		32,768	1024	24	6	1
16	65,536	98	113	130	136	143
20	1,048,576	122	137	154	160	168
24	16,777,216	146	162	178	184	192

Table 4. Potential increase in dynamic range,  $\Delta DR$ .  $F_s = 65,536$  Hz.

$\Delta DR$ , dB	Bandwidth, Hz			
	1024	24	6	1
	15	31	37	45

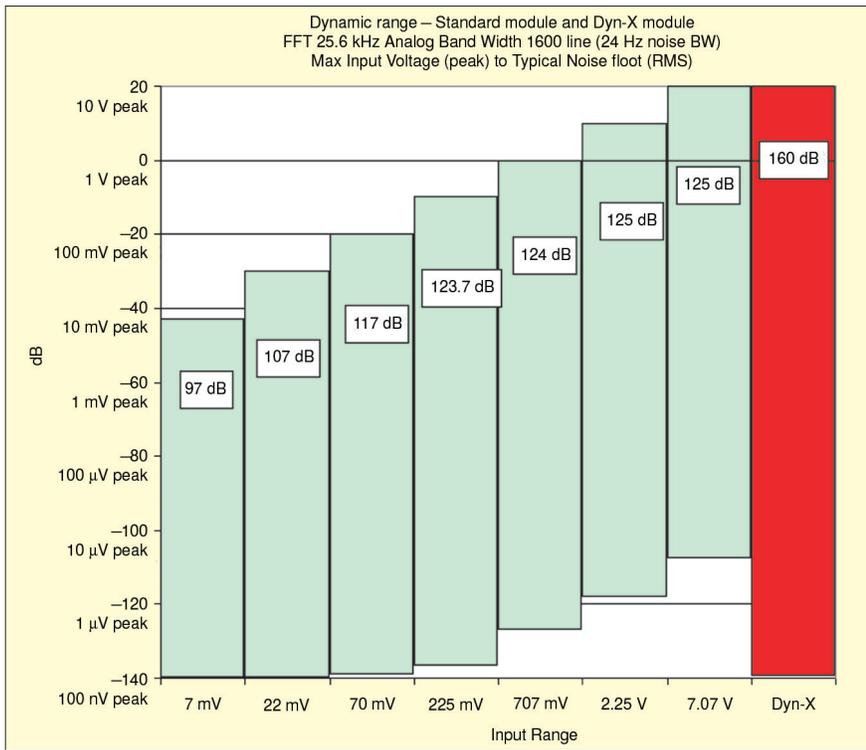


Figure 4. The dynamic range of a Dyn-X input channel (red) compared to the 7 ranges of a standard 24-bit input channel (green).

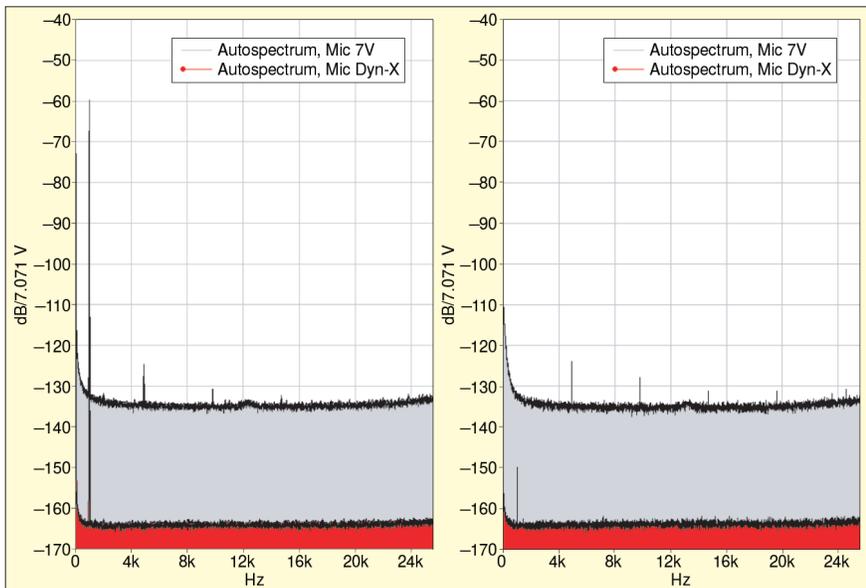


Figure 5. Comparison of Dyn-X input channel and 24-bit standard input channel, (left)  $-60$  dB ( $7$  mV)  $1$  kHz sine wave, (right)  $-150$  dB ( $0.22$   $\mu$ V)  $1$  kHz sine wave.

below  $-160$  dB for the Dyn-X input channel and the sine wave is easily detected. For the standard 24-bit input channel, the sine wave is buried in noise. Noise and ADC non-linearity are clearly visible in the standard channel.

In Figure 6, the Dyn-X input channel and standard 24-bit input channel are compared in the time domain for a  $1$  kHz sine wave attenuated  $90$  dB corresponding to a signal level of  $0.22$  mV<sub>rms</sub>. Again noise and ADC non-linearity are clearly visible in the standard channel.

**Office Noise Measurement.** In Figure 7, a 'real-life' office noise measurement example is shown. The measurement is per-

formed in a standard office environment with background speech and a person whistling; FFT analysis in  $25.6$  kHz,  $1600$  lines giving a frequency resolution of  $16$  Hz. The microphone signal is measured by both channels in parallel.

This simple measurement clearly illustrates the improved dynamics of the Dyn-X input channel when compared to a standard 24-bit input channel. The difference is close to  $30$  dB above  $4$  kHz. The 24-bit standard input channel is measuring system noise instead of environmental office noise.

**Conclusions.** 24-bit ADCs are today becoming an industry standard and, in

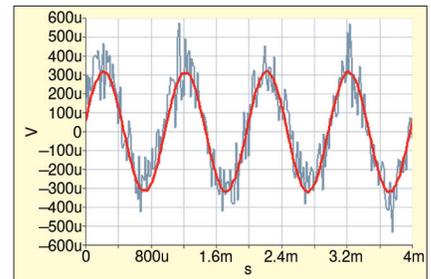


Figure 6. Comparison of Dyn-X input channel and 24-bit standard input channel for a  $-90$  dB ( $0.22$  mV)  $1$  kHz sine wave.

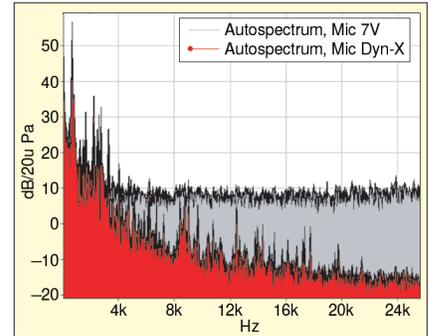


Figure 7. Comparison of Dyn-X input channel and 24-bit standard input channel.

theory, are able to handle the full dynamic signal range of high-quality transducers without the inclusion of an input attenuator. However, until now, no commercial ADCs have had sufficient performance to allow for elimination of the input attenuator. With the introduction of the new Dyn-X technology, a significant performance increase has been achieved in both analog conditioning and digital signal processing.

As demonstrated with measurement examples, the Dyn-X technology fully matches the high dynamic range of high-quality transducers, thereby totally eliminating the need for input attenuators. Consequently, measurements become safer, a higher measurement quality can be achieved and the operator does not constantly have to pay attention to the actual signal levels to avoid overload and under-range situations.

**Who Will Benefit?** Cutting-edge aerospace and automotive applications will benefit from Dyn-X technology, as it is ideal for applications when an accurate measurement has to be right the first time or many mixed transducers and unknown signal levels are involved, for example, crash testing, destructive testing, rotating machinery (run up/coast down), etc.

The new technology is also well suited for time limited applications such as test cells, wind tunnels, road testing, flight testing or high-dynamic range applications such as structural measurements, impulsive testing, room acoustics or electroacoustics.

For field or road testing, Dyn-X requires minimal user interaction and demands less personnel training for production line testing.

**References:**

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