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Practically Obtainable Dynamic Ranges of Data Acquisition Systems based on 24-bit Technology

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Abstract The linear operating range of high-quality measurement accelerometers and microphones has for many years been significantly better than that which can be achieved in 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, thereby theoretically being 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, the system operators must for a number of applications be very careful in optimizing the signal chain dynamics in order to avoid overload and underrange situations. This paper describes the high dynamic ranges that can be achieved in practice using today's state-of-the-art designs.

1. INTRODUCTION

This paper outlines the system performance that can be expected of present and future analysis systems. First some practical considerations regarding the potential dynamic range of high-quality transducers are given followed by a brief overview of the factors that reduce the system performance to less than the theoretical limit. Then, a few theoretical considerations regarding the potential dynamic range of a digital system, and the potential improvements when using narrowband analysis, are provided. Finally, a new technology optimizing the dynamic range of the system is introduced and illustrated with measurements showing system performance of 160 dB or more when using narrowband analysis.

2. DYNAMIC RANGE AND FREQUENCY RANGE

The ratio between the highest and lowest signal a system can handle is defined as the dynamic range of the system. If the dynamic range is too low, then 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:

$$DR = 20 \times \log \frac{V_{FS}}{V_N} \tag{1}$$

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 be introduced in either the time domain or the frequency domain, when performing narrowband analysis.

3. DYNAMIC RANGE OF TRANSDUCERS

For the last 30 to 40 years, sound and vibration transducers have outperformed the subsequent analysis systems as regards 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 to 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 µV to 15 µV in the audible frequency range and the max. 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.

Bandwidth [Hz]	25.6k	1.024	24	6	1
V_{FS} **[V_{RMS}]**	5				
V_N **[V_{RMS}]**	3µ	608n	93n	47n	19n
DR **[dB]**	124	138	154	160	168

Table 1: Dynamic ranges for a high-quality transducer

Throughout this paper a bandwidth of 25.6 kHz is used for broadband comparisons. For narrowband, comparisons 24 Hz, 6 Hz and 1 Hz are used, where e.g. 6 Hz corresponds to the effective noise bandwidth of a 25.6 kHz FFT analysis with 6400 lines using Hanning weighting [1].
So, a transducer can be used for narrowband measurements over a range of 160 dB (effective noise bandwidth 6Hz) 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 using narrowband analysis.

4. ANALYSIS CHAIN IMPERFECTIONS

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

Harmonic Distortion: Signals caused by non-linearities 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 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 Non-linearity: 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, which is not advantageous for input module designs. However, careful algorithm design can provide a very high dynamic range for the whole chain.

5. 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).

5.1 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 for 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 the limitations in the following DSP chain. The drawback is, however, a quite 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.

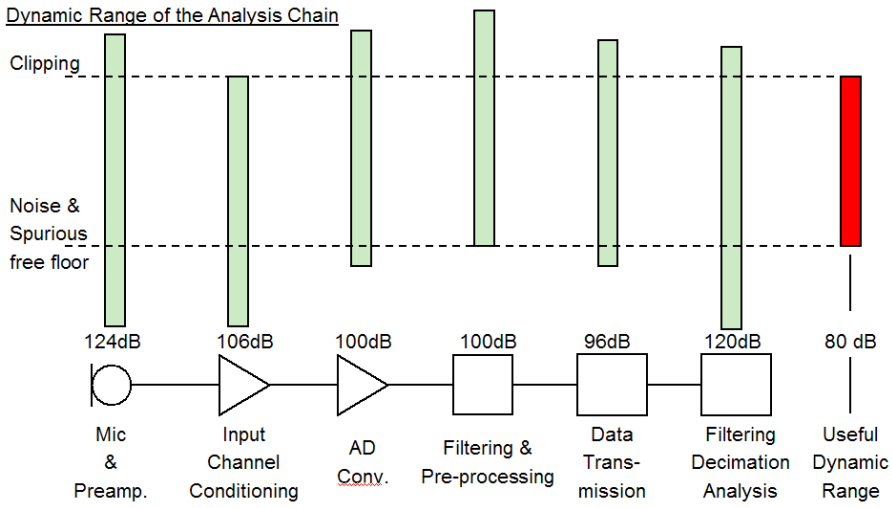


Figure 1 - Example of dynamic ranges of an analysis chain

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

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

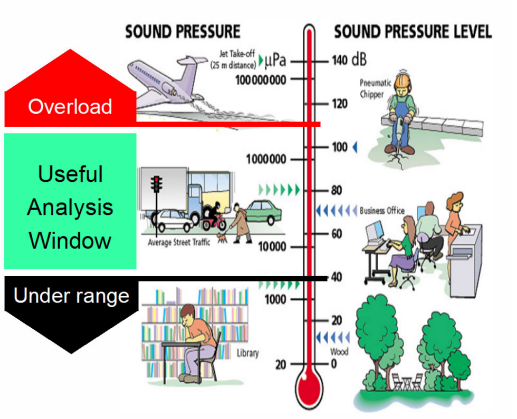


Figure 2: The effect of using an input attenuator illustrated for sound measurements

Overloads are probably the biggest cause of bad measurement results. It is becoming a still bigger issue in multichannel measurements 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.

5.2 Potential Dynamic Range of a 24-bit System

So how far can a system based on 24-bit quantization be taken? The following section gives some considerations on 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 [2]:

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

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

***N* [bits]**	**Resolution**	**Dynamic Range**				
		F_{NBW} [Hz]				
		32.768	**1.024**	**24**	**6**	**1**
16	65.536	98	113	129	135	143
20	1.048.576	122	137	154	160	167
24	16.777.216	146	161	178	184	191

Table 3: Dynamic ranges for different system quantization and bandwidth. F_s = 65.536 Hz

The theoretical increase in dynamic range ΔDR can be expressed as a ratio between the sampling frequency F_s and the width of the narrowband analysis F_{NBW} [2]:

$$\Delta DR = 20 \times \log \sqrt{\frac{Fs}{2 \times F_{NBW}}} \tag{3}$$

F_{NBW} [Hz]	1.024	24	6	1
ΔDR [dB]	15	31	37	45

Table 4: Potential increase in dynamic range, ΔDR. F_s = 65.536 Hz

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

6. NEW TECHNOLOGY INTRODUCTION

The above discussion shows that if ADC performance can be significantly improved in combination with a careful design of the whole analysis chain, then the problematic input ranging can be eliminated. Brüel & Kjær 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.

6.1 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. The digitizing is performed synchronously in two specially selected, high-quality, 24-bit ADCs and 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 no technical drawbacks should be introduced in either the time or the frequency domain with respect to distortion and other artifacts, when compared to existing designs.

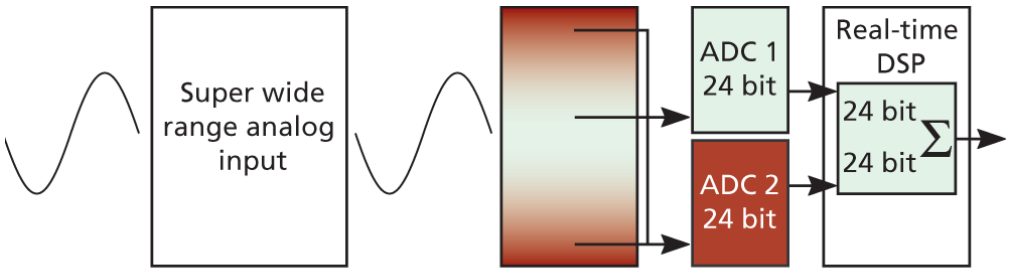


Figure 3: A simplified block diagram of the Dyn-X technology

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

6.2 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 the standard channel when set to a lower input range 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.

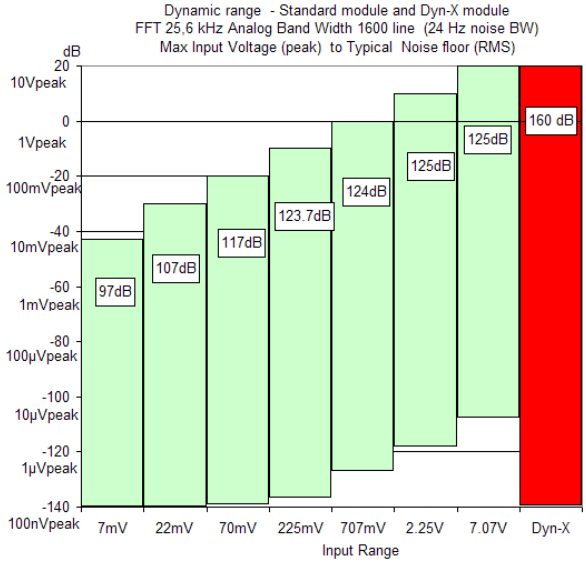


Figure 4: The dynamic range of a Dyn-X input channel (red) compared to the 7 ranges of a standard 24-bit input channel (green)

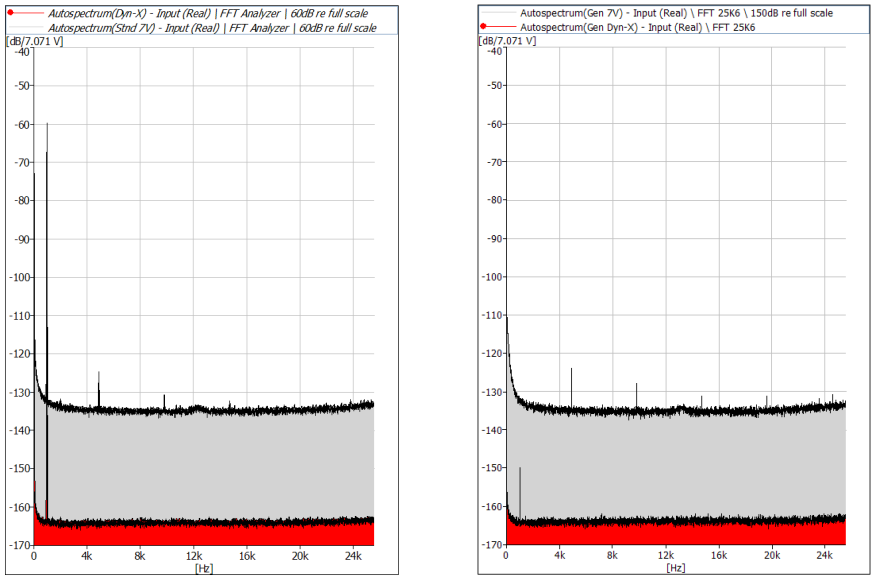


Figure 5: Comparison of Dyn-X input channel and standard 24-bit input channel
Left: –60 dB (7 mV_{RMS}) 1 kHz sine wave. Right: –150 dB (0.22 μV_{RMS}) 1 kHz sine wave

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 the 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 done, but now with the sine wave attenuated 150 dB corresponding to a signal level of 0.22 μV_{RMS}. The noise floor and the spurious components are 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_{RMS}. Again noise and ADC non-linearity are clearly visible in the standard input channel.

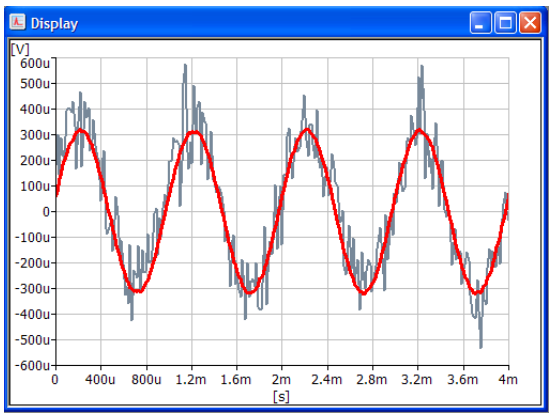


Figure 6: Comparison of Dyn-X input channel and standard 24-bit input channel for a –90 dB (0.22mV_{RMS}) 1 kHz sine wave

In Figure 7, a "real-life" microphone measurement example is shown. The measurement is performed in a standard office environment with background speech and a person whistling. FFT analysis is used in 25.6 kHz with 1600 lines giving a frequency resolution of 16 Hz. The microphone signal is measured by both channels in parallel.

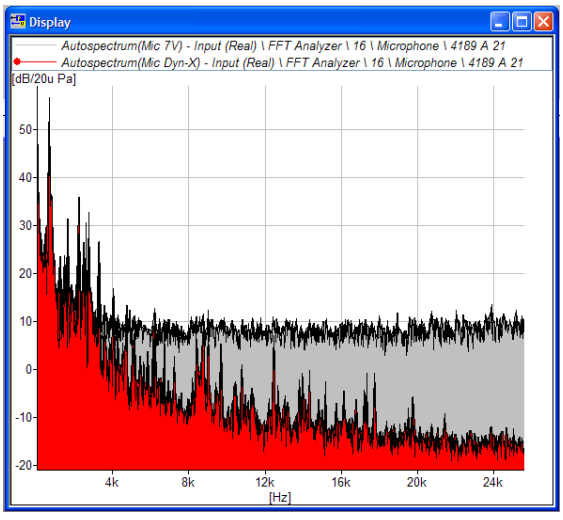


Figure 7: Comparison of Dyn-X input channel and standard 24-bit input channel Microphone measurement in office

This simple measurement clearly illustrates the improved dynamics of the Dyn-X input channel when compared to the standard 24-bit input channel. The difference is close to 30 dB

above 4 kHz. The standard 24-bit input channel is measuring system noise instead of environmental office noise.

7. CONCLUSION

For the last 30 to 40 years, high-quality transducers have outperformed analysis systems as regards linearity and dynamic performance. Several weak links in the analysis chain have reduced the resulting analysis performance and an input attenuator has been required to accommodate the dynamic signal range of the transducer. This increases the risk of overload and underrange situations in many practical measurement situations and it forces the user to constantly pay attention to the measurement status.

24-bit ADCs are today becoming industry standard and, as has been shown in this paper, they are in theory 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, significant performance increase has been achieved in both the analogue conditioning and the digital signal processing. As demonstrated with measurement examples, 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 underrange situations.

REFERENCES

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