ASEC 2025 Conference
The 6th International Electronic Conference on Applied Sciences
09–11 December 2025 | Online
MDPI

Modeling the Influence of ADC Transfer Function Nonlinearity on the Spectral Characteristics of Digital Signals

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INTRODUCTION & AIM

Modern digital measuring instruments — such as oscilloscopes, multimeters, and spectrum analyzers — rely on analog-to-digital converters (ADCs) to digitize signals for analysis. However, real ADCs exhibit non-ideal behavior due to nonlinearity in their transfer function. This nonlinearity may cause signal distortion, measurement inaccuracies, and spectral contamination, especially in high-precision applications.

ADC transfer function nonlinearity includes **integral nonlinearity (INL)** and **differential nonlinearity (DNL)**, which are typically specified in ADC datasheets. However, these values do not fully describe the distortion introduced into a specific signal during sampling.

Aim: To analyze the influence of ADC transfer function nonlinearity—particularly INL—on the spectral characteristics of digitized signals through simulation-based modeling and spectral analysis.

METHOD

For real ADCs, this relationship is distorted due to nonlinearity:

$$y = x + \Delta_{LIN}(x),$$

where $\Delta_{LIN}(x)$ is the nonlinearity error of the ADC transfer function.

Integral nonlinearity (INL) is defined as:

$$INL\square\, q = \max(\Delta_{INL}(x)),$$

where $q = U_{REF}/2^{N_{ADC}-1}$ — the least significant bit (LSB),
N_{ADC} — the ADC bit resolution including the sign bit,
U_{REF} — ADC reference voltage.

The research combines theoretical analysis with simulation experiments. The conversion function of an ideal ADC is assumed to be linear, while the real conversion function includes an INL component modeled as a sinusoidal deviation.

Simulation parameters:

- Input signal: 10 Hz sinusoid
- Duration: 1 second
- Sampling frequency: 1000 Hz
- ADC resolution: 12 bits
- INL modeled as sine-shaped distortion ranging 0-20%
- Quantization performed after INL distortion
- FFT applied to evaluate spectral characteristics

The resulting transfer function deviation causes harmonic distortion in the output signal, observed as changes in spectral content, especially the reduction of the fundamental frequency amplitude.

FUNDING

Funded by the EU Next Generation EU through the Recovery and Resilience Plan for Slovakia under the project No. 09I03-03-V01-00104.

RESULTS & DISCUSSION

The modeling confirms that INL introduces significant spectral distortion. As the INL amplitude increases, the amplitude of the fundamental frequency (10 Hz) decreases due to redistribution of signal energy into harmonic components.

This confirms theoretical assumptions: INL leads to nonuniform quantization intervals and loss of signal fidelity. It also highlights the need for ADC compensation or correction algorithms in high-accuracy applications.

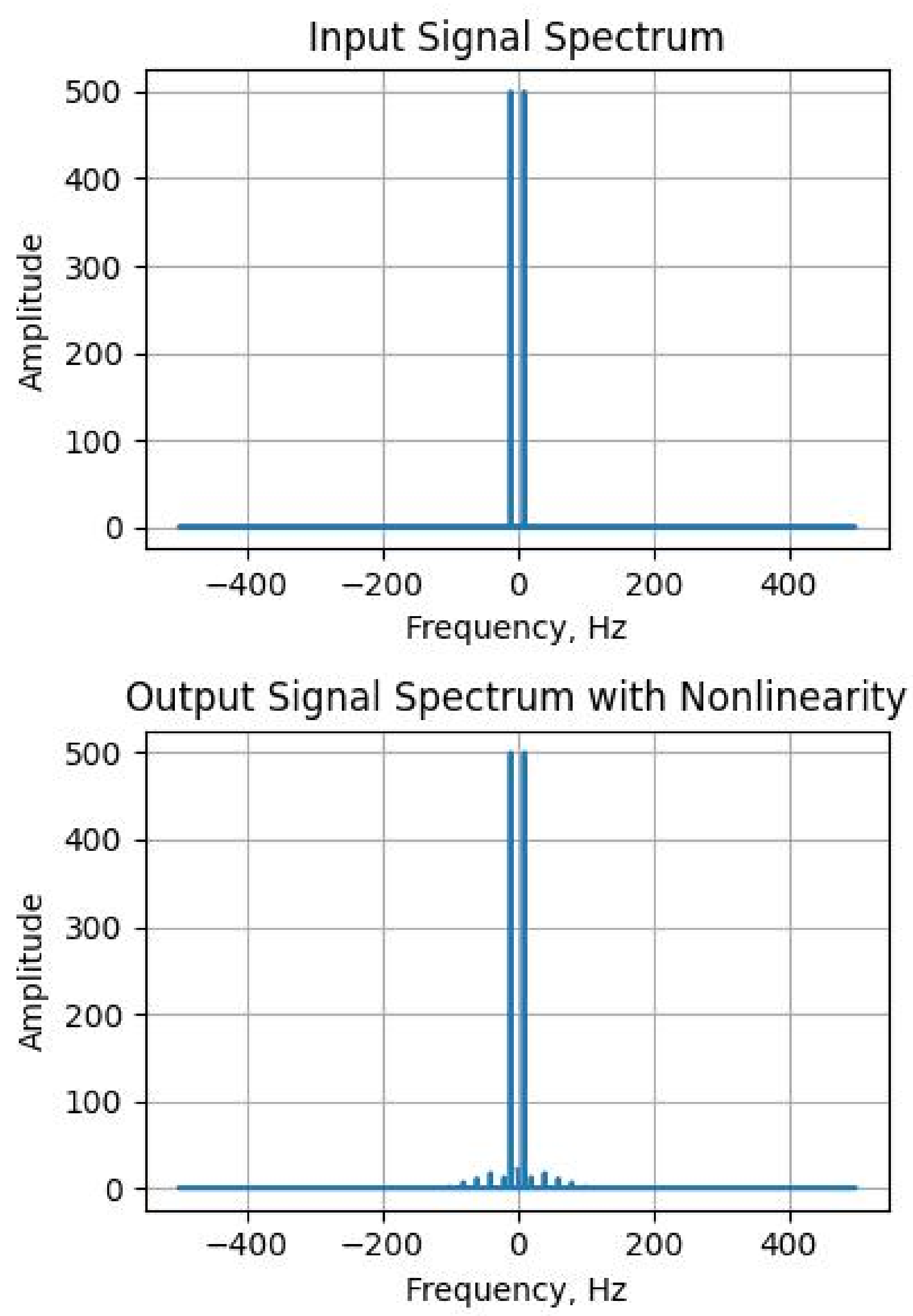

Figure 1. Amplitude spectrum of the ideal input signal (top) and the output signal after ADC with 10% integral nonlinearity (bottom). The nonlinear distortion causes the appearance of additional harmonic components.

CONCLUSION

ADC transfer function nonlinearity can cause signal degradation even in ideal input conditions. The findings underscore the importance of understanding and compensating for INL effects in measurement systems. Further research will include experimental validation and modeling of DNL effects.

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