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Understanding the Aliasing Effects of Delta-Sigma Analog to Digital Converters

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ABSTRACT

An experiment was conducted to evaluate the performance of a delta-sigma data acquisition system. The principle of the delta-sigma analog to digital converter is to over sample the signal, measure the error, integrate, and then compensate for the error. The purpose of the experiment was to determine if data collected from a delta-sigma converter could be susceptible to aliasing. This paper will present the results of an aliasing experiment and will provide recommendations for preventing aliasing when using delta-sigma converters.

INTRODUCTION

In the research and development world, collected data needs to be of high quality and high reliability, and one long standing concern of test engineers in the dynamic data acquisition community is aliasing of data. Aliasing of data can ruin test data and have a serious negative impact to a program in terms of time and money. For this reason, the practicing test engineer must understand how aliasing can affect their data, and how data acquisition systems protect against aliasing.

Although the delta-sigma modulator was first introduced in 1962, delta-sigma analog to digital converters (ADC) have only recently been a common tool used to collect high fidelity, high sample rate data in research and development settings [1]. Previous ADC types used include successive approximation and flash type converters, which require a complicated analog low pass filter on the front end of the ADC to combat aliasing [2]. Delta-sigma converters enable the use of a much simpler design to achieve similar results.

This paper will provide a brief review of aliasing in test data, with particular attention to the importance of analog anti-aliasing filters used on the front end of modern data acquisition systems. In addition, a description of high fidelity delta-sigma ADCs will be given. Test data will be presented that addresses the concern of aliasing while using a 16 bit delta-sigma ADC, and recommendations will be made based on the test results.

REVIEW OF ALIASING

Aliasing is an artifact that occurs when data is not properly bandwidth limited before the data is sampled. Aliasing may occur any time a continuous signal is sampled at discrete instants in time. In addition, aliasing may also occur when data is improperly down sampled. Aliasing effects are nonlinear and non-recoverable, which prompts test engineers to be incredibly careful in preventing aliasing in the first place. The catch-all key to preventing aliasing in a conventional ADC system is to use an analog low pass filter with a flat response in the frequency range of interest and attenuate the frequencies above half of the sampling frequency, also known as the Nyquist frequency [2,3]. The anti-aliasing filter should be placed on the "front end" of the data system, which means the signal should be filtered before it is digitized, i.e. bandwidth limited before sampled.

The sample rate that a system uses and any down sampling that may be performed by the system is of particular concern with regards to aliasing. These two concerns were chosen here as they have a direct correlation to the inner workings of a delta-sigma type ADC. Two examples were chosen to review the concepts of anti-aliasing filters and their effects on test data.

Sample rate is a significant driver in determining the bandwidth of a data acquisition system. The bandwidth would be defined as the Nyquist frequency, or half of the sampling rate. Figure 1 shows two sine wave signals with frequencies of 10 Hz and 90 Hz. The signals have been digitized with a sample rate of 1000 Hz which has a Nyquist frequency of 500 Hz. Sampling theorem dictates that the spectral content of each signal will be preserved because the highest frequency content in each signal is below the Nyquist frequency. Figure 1 clearly illustrates that each signal is well represented in the time domain. Figure 2 shows the same two input signals sampled at a rate of 100 Hz without an anti-aliasing filter. The 90 Hz input signal has been aliased, and appears as a 10 Hz signal that is out of phase with the original 10 Hz signal. Figures 1 and 2 illustrate the dependence of bandwidth on sample rate and the importance of using an anti-aliasing filter.

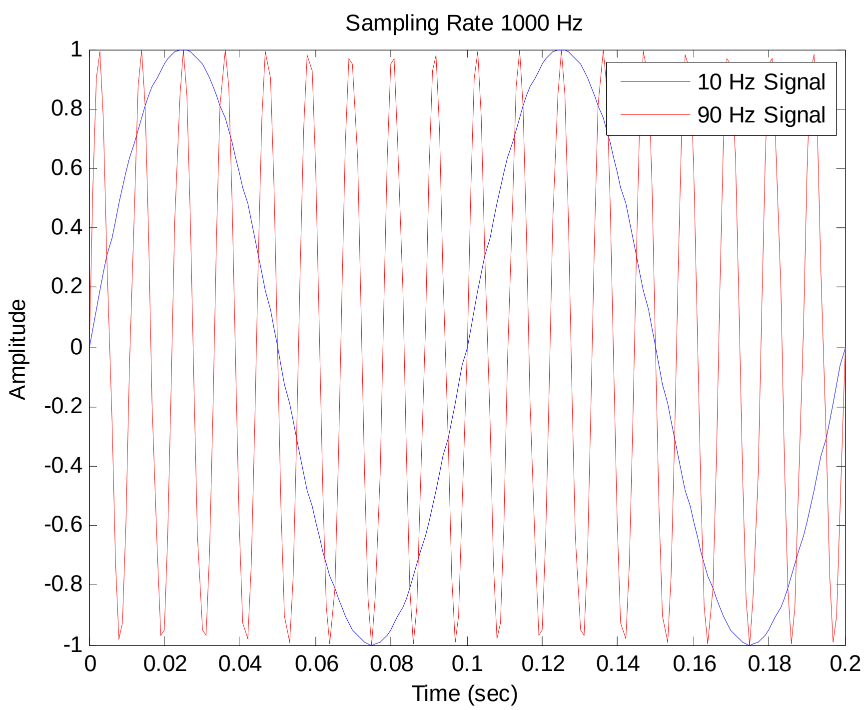

Figure 1. Well represented Signals.

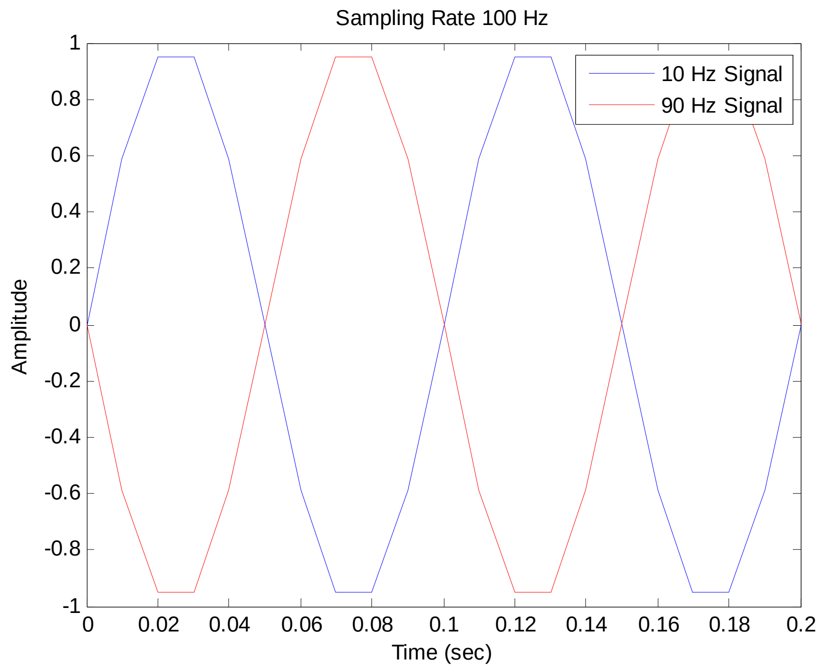

Figure 2. Aliased Signals.

Down sampling is another operation that is susceptible to aliasing data if the signal is not bandwidth limited. As an example, consider a signal with four prominent components in the frequency domain: 250 Hz, 600 Hz, 1400 Hz, and 2000 Hz. Assume a sample rate of 10 KHz and a corresponding Nyquist frequency of 5 KHz. Figure 3 shows the Fast Fourier Transform (FFT) of the signal in blue, with peaks at the corresponding frequency contents. Also shown are the FFT plots of the same signal down sampled by a factor of 4 (red), and low pass filtered at 1.25 KHz and then down sampled by a factor of 4 (green). Down sampling the signal without first filtering aliases the signal, as the evidence shows in Figure 3 by additional red peaks in the FFT.

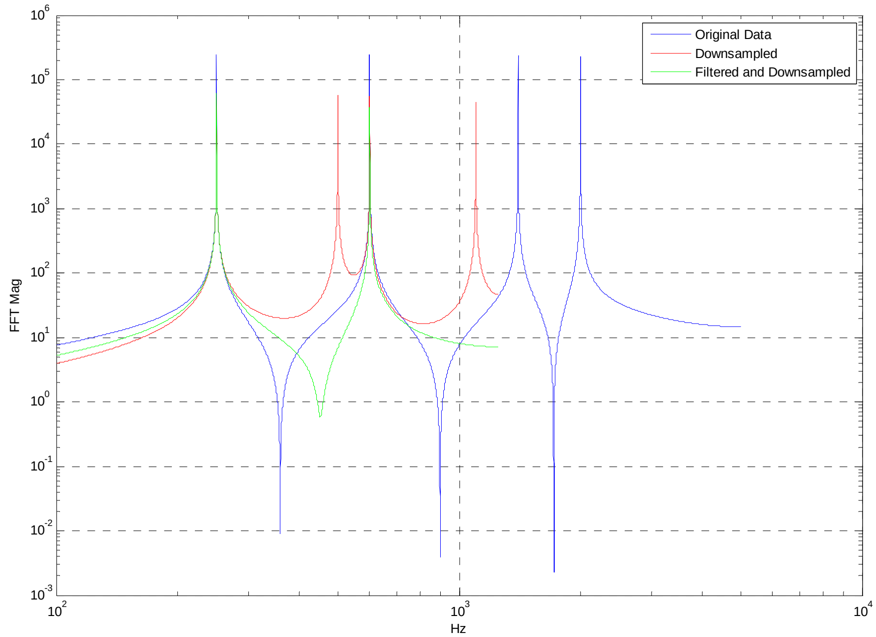

Figure 3. Down Sampling Example.

DELTA-SIGMA CONVERTERS

Delta-sigma ADCs work on the principle of over sampling with one bit resolution, then low pass filtering and down sampling to decrease the effective sample rate and increase the fidelity of the data. Over sampling effectively spreads a fixed amount of quantization noise over a very large bandwidth, and through delta-sigma modulation attenuates the noise in the bandwidth of interest and amplifies outside the bandwidth of interest [4]. The decimation process attenuates the out of band noise and reduces the effective sample rate. Many different types of delta-sigma modulation have been implemented, some of which are currently in use in structural dynamics laboratories [4].

A benefit of over sampling, modulating, and decimating is that the anti aliasing filter does not require a high quality sharp cutoff at the Nyquist frequency. A simple RC circuit can be used as a filter, such that the roll off attenuates sufficiently somewhere between the effective Nyquist frequency, f_B, and the over sampling rate, f_S. The design of the RC filter creates regions of interest in terms of potential aliasing effects. The RC filter attenuation pattern is shown in Figure 4 with the regions of interest, including the “Pass Band” and “Band Rejected by Design”. The Pass Band is defined as the region between zero and the effective Nyquist frequency. The Band Rejected by Design is defined as the region between the effective Nyquist frequency and the over sampling rate. Additionally, the transition zones located at the bandwidth edge and the over sampling rate are also potential zones for aliasing.

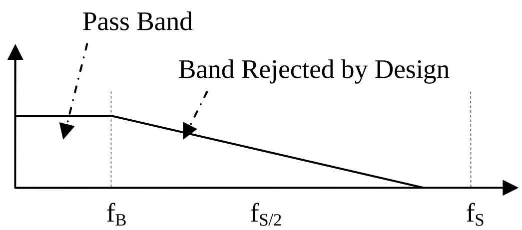

Figure 4. RC Anti-Aliasing Filter Response and Corresponding Frequency Bands.

TEST PLAN AND TEST RESULTS

The motivation for this project was to determine if delta-sigma systems were susceptible to aliasing. To determine if these systems are in fact susceptible, a test plan was devised to input a signal into the ADC and determine if any aliasing occurs. The input frequencies were chosen based on anti alias filter and the system characteristics.

The system currently used in the Sandia National Laboratories Area I Mechanical Shock Laboratory is a VXI based Spectral Dynamics Sigma-Delta ADC (note: Sigma-Delta and Delta-Sigma are defined as the same in the literature). The system has an over sampling rate of 22 MHz and is decimated to 2.5 MHz with a bandwidth limited to 1 MHz.

Figure 5 shows the resulting FFT from generating three sine waves with three different frequencies in the Pass Band range. Each signal is well represented in the frequency domain. Figure 6 shows the resulting FFT from four sine waves near the bandwidth edge of 1 MHz, with frequencies of 0.9, 1.0, 1.1, and 1.25 MHz. The figure shows each signal, even those outside of the published bandwidth, as un-aliased. The 1.25 MHz sample begins to show some attenuation due to the low-pass filter used in the decimation process. Resulting FFTs for signals in the Rejection Band and near the over sampling rate were typical of white noise inputs, with flat spectrums over the bandwidth.

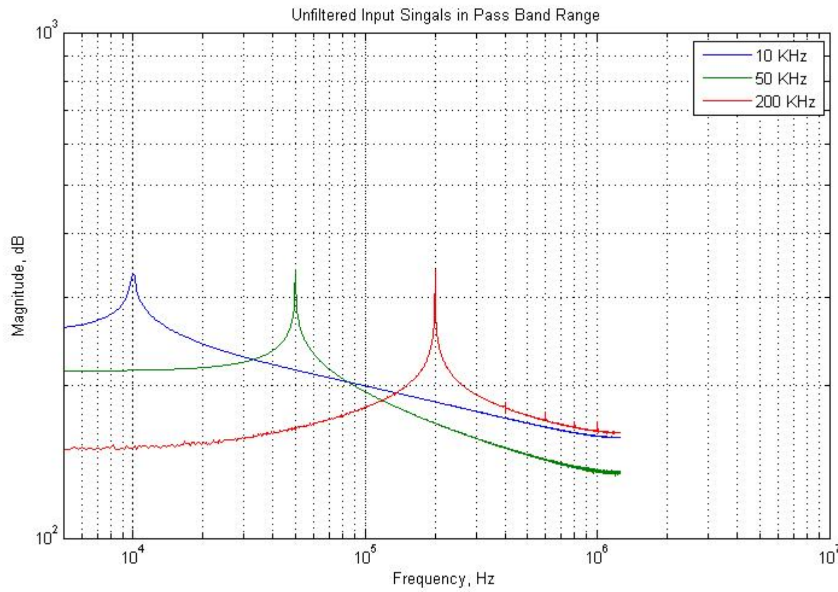

Figure 5. FFT of Signals in "Pass Band" Region.

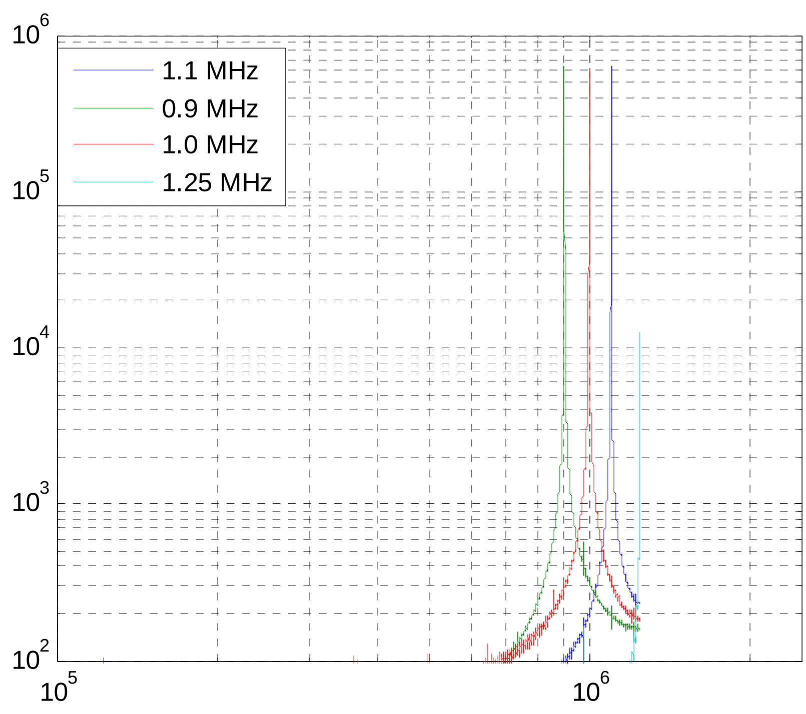

Figure 6. Signals Near Bandwidth Edge.

CONCLUSIONS AND RECOMMENDATIONS

An explanation of how over sampling delta-sigma ADC work leads to understanding the potential aliasing effects of the digitization process. The over sampling, modulation, and decimation process lends itself to a simple anti-aliasing solution in the form of a simple RC circuit type filter with the advantage of having a long bandwidth in which to properly attenuate the signal. This is a huge advantage over the anti-aliasing filter characteristics needed to adequately protect traditional ADCs.

The results indicate that the VXI based Spectral Dynamics data acquisition system does protect data from becoming aliased through the analog RC circuit serving as the anti-aliasing filter, combined with the decimation process. The input signals in each range and near each transition were either correctly represented or adequately filtered out. These results indicate that no additional analog anti-aliasing filters are required on the front end of the data system for protection.

ACKNOWLEDGEMENTS

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REFERENCES

1. Inose, H., Y. Yasuda, and J. Marakami, "A Telemetering System by Code Modulation, Delta-Sigma modulation," *IRE Trans. On Space, Electronics and Telemetry,* SET-8, pp. 204-209, Sept 1962.

2. Park, S., "Principles of Sigma-Delta Modulation for Analog-to-Digital Converters," Motorola Report APR8/D.

3. Beckwith, T.G., R.D. Marangoni, and J.H. Lienhard V, 1995, *Mechanical Measurements*, Addison-Wesley Publishing Company, Inc., Reading, Massachusetts.

4. Aziz, P.M., H.V. Sorensen, and J. Van Der Spiegel, "An Overview of Sigma-Delta Modulators," *IEEE Signal Processing Magazine*, 1996, Vol. 13, pp. 61-84.