Derivative-Based Quadrature Identification of Channel Delays

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Abstract – Real-time detection of phase or time delay between two ADC sample channels, especially when fractional-delay filter is involved, often uses quadrature-filter, which may not be cost-effective since two filter channels have to be constructed to deal with each live ADC sample stream. This paper presents a phase delay quadrature detection method based on derivatives of the sample stream. The challenge is to deal with the inherent detection error of the naïve derivative when high normalized frequency has to be used in RF/IF applications. The cause of the error is analyzed, and a proprietary algorithm is developed to cancel the error at the critical quadrature crossing boundary, namely 0, ±90 and ±180 degree.

Keywords: phase delay, quadrature, derivative, fractional-delay filter, real-time, cost-effective.

1 Introduction

The phase of a complex waveform described as
\[ A \angle \phi = I + jQ \]  \hspace{1cm} (1)
can often be obtained by
\[ \phi = \text{atan}(|Q|/|I|) \]  \hspace{1cm} (2)

If the waveform is passing through a digital signal processing (DSP) device: ADC sampled, filtered, two filters (I and Q) have to be constructed, which may not be cost-effective in some applications. Fig.1 illustrated a real application, in which a waveform [1] is received from a radar front-end processing unit, with wide dynamic range. Since the ADC doesn’t have enough dynamic range to match the signal’s range, the signal is “split” into two ADC channels, with one channel deals with attenuated signal, so the overall system will not saturate when input signal reaches its highest level. During the pre-processing, the original signal maybe also has been phase transformed (separated) in these two channels, besides the intended gain separation. Before merging into an output signal that ideally has the same characteristics of the original signal, both the intended gain separation and unintended phase separation must be corrected. The phase correction is done through a reconfigurable fractional-delay finite impulse response filter (RFDFIR) [2][3], together with a phase sensitive detection (PSD) module. To construct two separate I and Q filters for both the high and low gain channels will significantly increase the implementation cost: the FPGA area budget within a radar video processing (RVP) [4] device.

Fig 1. An example application where phase detection with complex filters (I, Q) is not cost-effective.
A novel real-time detection of phase delay over ±180 degree range without using IQ filter is presented in the following. Section 2 describes the challenge of using naïve derivative method, the inherent quardarature detection error when very high normalized frequency has to be used in radar IF domain. A proprietary algorithm is used to counter the naïve quadrature detection error by realizing that it is the quadrature identification itself instead of the absolute error affects the accuracy of overall phase detection. Section 3 presents a real-life application result and further discussions are in Section 4.

2 Derivative-Based Detection

2.1 Fundamentals of Naïve Derivatives

To cover the full range, ±180 degree angle phase (delay) detection, the quadrature information of the angle can be derived from the cosine alone. When the angle detected from asin term (which covers 0~±90 degree) is known, the actual phase can be deduced as:

\[ \phi = (\cos > 0) \cdot \text{asin} (\sin > 0) \cdot (180 - \text{asin} (\text{sin} < 0)) \cdot (180 - \text{asin} (\text{sin} > 0)) \]  

Fig. 2 shows the identification of quadrature. Note that only the sign of the cosine term, not necessary its accurate value is needed to identify the quadrature correctly, as long as the quadrature crossing critical points, namely the ±90 boundaries can be identified uniquely.

The cos term can be derived by using derivatives of the incoming waveform stream, especially in baseband sampling, where the normalized frequency is low, or equivalently, the ADC sampling frequency is far higher than signal frequency – as a result, many samples per cycle can be sampled and used to calculate the derivative; or the sampling period, T, is relatively very short, as defined mathematically:

\[ \cos(t) = \frac{\sin(t+\Delta t) - \sin(t)}{\Delta t}, \Delta t \to 0, \Delta t \text{ as } T \]  

But in RF/IF signal processing, quite often bandpass sampling, where low sampling frequency is used. Even processing at aliasing frequency, the normalized frequency is still very high. Fig. 3 shows an example, where a 60MHz IF signal is sampled at 72MHz. Only 6 samples per cycle can be obtained even at the relatively lower aliasing frequency (12MHz). Therefore the assumption in equation (4) is not valid and considerable error will be resulted for the derivative, as shown in Fig. 4: the phase error between the ideal derivative (when T is tiny, shown in cyan) and the actual one (when T is corresponding to 60 degree, shown in red) is corresponding to about half of the sampling period.
2.2 Improved Derivative and Phase Detection

The derivative error is a function of sampling frequency, as shown in Fig. 4, or more precisely, of normalized frequency. It is also related to the relative phase delay itself when used for phase/time delay detection; in this case, both the sin and cos terms can be deduced using cross correlation of the two channel waves, as shown in Fig. 1. The derivative error around the critical boundary-crossing points (i.e., ±90 degree) can be reduced by using a proprietary algorithm, as shown in Fig. 5.

As indicated in section 2.1, only the sign of cosine term is used to identify whether the phase is to the left or right of the quadrature plane (Fig. 2), not the absolute phase (acos) value, so the results shown in Fig. 5 is not surprising. Although the acos value around the phase 0 and ±180 degree is far off from the actual (about 30 degree error), the quadrature (left/right) can still be correctly identified based on the sign of cosine. For example, around phase angle 0, the acos produces value as about 30 degree instead of 0, but the sign of cos(0) and cos(30) are the same, i.e., positive (+); around the phase ±180 degree, the acos produces value as around 150 degree instead of 180, but both have the same sign in terms of cos so they will not affect the quadrature identification either. Around the critical ±90 degree, where the sign of cos term is abruptly switching, the derivative method produces smooth angle transition, error nearly as zero, as clearly shown in Fig. 5.

3 An Example of Derivative-based Phase Delay Detection

As shown in Fig. 1, waveforms from two channels can have intended gain separation and unintended phase/time delay separation [1]. The waveforms are shown in Fig. 6. Both the gain and phase delay can be detected and then adjusted before merging into a wider dynamic range.
When derivative-based phase detection is used, the detected phase are used to generate a new set of FIR coefficients for both high and low gain channel to make the filtered output phase aligned before merging – a matter of simple switch between these two channels to use only unsaturated output from corresponding channel. One criterion to judge the accuracy of both phase detection and correction is the phase noise of the merged waveform – ideally perfectly aligned. Fig. 7 shows the merged waveform, with a general noise power (high gain channel relative to low gain channel) of -60dB.

4 Further Discussions

The accuracy of phase delay detection is fundamentally based on cross-correlation of two channels, where the number of total correlated samples used will play an important role, depending on the channel noise. This is more important for the derivative-based cosine term detection than the sine term itself, as seen from equation (3) at the critical boundary crossing angle ±90 degree.

Besides using more correlated samples, in a closed-loop system, more iteration may be used to remedy inadequate accuracy of cosine term detection around the critical point to control the system in a stable state.

5 References


Fig 7. The merged waveform using derivative-based phase detection