THE STUDY OF I-Q SIGNAL GENERATION USING COMPLEX FILTER BASED ΔΣ D/A MODULATOR FOR COMMUNICATION APPLICATION

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ABSTRACT
This paper describes the study of application of a complex bandpass ΔΣ D/A modulator as Quadrature (I-Q) signal generation in communication systems for communication Integrated Circuit (IC) testing as well as transmitter. The study shows that the complex bandpass ΔΣ D/A modulator is superior compared to two real-bandpass ΔΣ D/A modulators regarding to noise-shaping characteristics. Hence, the trade-off between bandwidth and sampling speed is better for the complex bandpass ΔΣ D/A modulator. This study also presents the theoretical analysis and simulation results of its extension and complex multi-bandpass modulator characteristics. From the result,

Keywords: complex filter, complex bandpass, multi-band, D/A modulator.

INTRODUCTION
Demands for low cost, low power and high performance of a digital-to-analog (D/A) (Figure-1) converter are significantly increased especially in communication applications. Since communication devices become inexpensive and more sophisticated, the D/A converter circuits in their transmitter parts (which often generate I-Q signals) become more complicated and challenging. Nevertheless, the Very Large Scale Integration (VLSI) fabrication cost reduces with the advancement of VLSI process technology. The successful market of the portable devices is also a factor that contributes to the high demands of low cost and high performance of D/A converter. Most of these devices also require a low power D/A converter to allow them operate at operating voltage which mostly uses battery.

On the other hand, the testing cost of a IC device increases due to the circuit complexity and high specification requirements. The testing of the communication ICs requires high quality I-Q signal at low cost, and in many cases, D/A converters used to produce I-Q signal generation (Vasan et al., 2012), (Abe et al., 2014), (Khafaji et al., 2014). This paper discusses applicability of a complex bandpass ΔΣ D/A modulator to generate I-Q signals rich configuration.

D/A CONVERTER FOR I-Q SIGNAL GENERATION
This section discusses advantages and drawbacks of the existing architectures for I-Q signal generation. The architectures can be classified as follow:

1) Analog method.
2) Digital method (DSP + D/A converters, or Direct Digital Synthesizer).
   2-1) DSP + two Nyquist-rate D/A converters + two analog filters.
   2-2) DSP + two real-bandpass ΔΣ D/A converters + two analog filters.
   2-3) DSP + one complex–bandpass ΔΣ D/A converter + one analog complex filter.

As the VLSI technology progresses, digital method becomes much easier to design. The method 2-1) requires relatively large Nyquist-rate D/A converters and analog filters. The method 2-2) uses two digital ΔΣ D/A converters whose circuits are negligible in fine Complementary Metal Oxide Semiconductor Large Scale Integration (CMOS LSI) and one 1-bit D/A converter (which are also negligible), and also requirements for two analog filters can be relaxed due to the oversampling. The same arguments hold for the method 2-3) as those of the method 2-2).

Figure-2 shows block diagrams for the methods 2-2) and 2-3). Up-conversion mixers with local oscillators may follow the analog filters in the digital methods (Otsuki et al., 2005).

COMPLEX BANDPASS ΔΣ D/A MODULATOR FOR I-Q SIGNAL GENERATION

Figure-1. D/A converter with its input and output signals.
Figure-2. I-Q signal generation with ΔΣD/A modulation. (a) Two real-bandpass modulators (method (2-2)) and (b) One complex bandpass modulator (method (2-3)).

Figure-3. Noise-shaping characteristics. (Left) Real bandpass modulator. (Right) Complex bandpass modulator.

Now let us compare the methods 2-2) and 2-3). Suppose that the centre of the I-Q signal band is \(-f_s/4\). Then as Figure-3 shows, the noise-shaping characteristics for the complex modulator around \(-f_s/4\) is better than that of the real bandpass modulators (in other words, the quantization noise in the signal band is lower in complex modulator case).

The complexity of two real analog filters and one analog complex filter would be comparable. Hence, the method 2-3) (which uses complex signal processing) would be better than the method 2-2).

Remark: One might argue that better noise-shaping characteristics can obtain higher-order real bandpass modulators and digital modulators are free in fine CMOS LSI. However, higher-order modulators require higher-order analog filters following the modulators, and hence comparison of complex and real bandpass modulators with the same order would be fair.

COMPLEX BANDPASS ΔΣD/A MODULATOR

This section describes the complex bandpass ΔΣD/A modulator in details. Figure-2 and Figure-3 show the illustration of advantages of a complex bandpass ΔΣD/A modulator compared to two real bandpass ΔΣD/A modulators. By using this type of modulator, larger bandwidth (or better Signal-to-Noise Ratio (SNR)) can be obtained due to its asymmetric behaviour with respect to \(\omega_c = 0\). In contrast, the real bandpass modulator has a symmetric behaviour with respect to \(\omega_c \neq 0\) with two poles at two different points and it provides only a half bandwidth for each pole (Otsuki et al., 2005), (Shreier and Temes, 2005), (San et al., 2007), (Martins, 2004), (Kobayashi et al., 2002).

Complex bandpass filter

Figure-4(a) shows the structure of a basic complex filter.

Figure-4. (a) Complex filter and (b) its gain characteristics.

From Figure-4(a), the gain of the system can be determined by obtaining their transfer function (Figure-4(b))? First, the equations derived from inputs to outputs as follows:

\[
I_{out}(z) = I_{in}z^{-1} - \alpha Q_{out}z^{-1} + \beta I_{out}z^{-1} \quad (1)
\]

\[
Q_{out}(z) = Q_{in}z^{-1} + \alpha I_{out}z^{-1} + \beta Q_{out}z^{-1} \quad (2)
\]

Next, complex input \(V_{in}(n)\) and complex output \(V_{out}(n)\) as follows:

\[
V_{in}(z) = I_{in}(z) + jQ_{in}(z) \quad (3)
\]

\[
V_{out}(z) = I_{out}(z) + jQ_{out}(z) \quad (4)
\]

Then, its transfer function, \(H(z)\) is defined as follows:

\[
H(z) = \frac{V_{out}(z)}{V_{in}(z)} \quad (5)
\]

Finally, the transfer function obtains as:

\[
H(z) = \frac{1}{z - (\beta + j\alpha)} \quad (6)
\]
Complex bandpass ΔΣ D/A modulator

Figure-5(a) and Figure-6(a) show first-order and second-order complex bandpass ΔΣ D/A modulators with the centre frequency \(-f_s/4\) of the signal band. Figure-5(b) and Figure-6(b) show their output spectrum for the complex sinusoidal signal input around \(-f_s/4\), and it is shown that the quantization noise is shaped at \(-f_s/4\). Here, value of \(\alpha=1\), \(\beta=0\) is used.

**Figure-5.** First-order complex bandpass ΔΣ D/A modulator.

**Figure-6.** Second-order complex bandpass ΔΣ D/A modulator.

**COMPLEX MULTI-BANDPASS ΔΣ D/A MODULATOR**

This section describes complex multi-bandpass ΔΣ D/A modulators for multi-tone I-Q signal generation (Motozawa et al., 2007).

**Complex multi-bandpass filter**

Figure-7 shows a first-order complex multi-bandpass filter, and Figure-8 shows its gain characteristics for (a) \(n=2\) and (b) \(n=4\).

Its transfer function given as follows:

\[
H(z) = \frac{1}{z^n(\beta+j\alpha)}
\]

(7)

**Figure-7.** Complex multi-bandpass filter.
Complex multi-bandpass $\Delta\Sigma$D/A modulator

Figure-9 and Figure-10 show first-order and second-order complex multi-bandpass $\Delta\Sigma$D/A modulators, and Figure-11 shows the simulated output power spectrum for the second-order with (a) $n=2$ and (b) $n=4$. Figure-12 shows SNR versus OSR (oversampling ratio).

Figure-8. Gain characteristics of multi-band complex filters.

Figure-9. First-order complex multi-bandpass $\Delta\Sigma$D/A modulator.

Figure-10. Second-order complex multi-bandpass $\Delta\Sigma$D/A modulator.

Figure-11. Second-order complex multi-bandpass $\Delta\Sigma$D/A modulator output spectrum.

Figure-12. Simulated SNR versus OSR for second-order complex multi-bandpass $\Delta\Sigma$D/A modulators.
SIMULATION RESULT

The performance of complex compared to real bandpass modulator is verified using MATLAB simulator. For comparison study, a second-order complex modulator in Figure-6, and a second-order real bandpass modulator in Figure-13 is simulated. The simulation results show their noise-shaping behaviours in Figure-14(a) and Figure-14(b) for both real and complex bandpass respectively, and their OSR versus SNR performance as shown in Figure-15. As a result, the second-order complex modulator has better SNR by 10dB compared to the second-order real bandpass modulator.

Figure-13. A second-order real bandpass ΔΣD/A modulator used for simulation.

By set the value of \( a_1, a_2 \) and \( b \) as follow:

\[ a_1 = 1, \quad a_2 = 1, \quad b = 2 \]

The Signal Transfer Function (STF), \( STF(z) \) is defined as:

\[ STF(z) = \frac{a_1 a_2 z^{-2}}{D(z)} \]  

Then, the Noise Transfer Function (NTF), \( NTF(z) \) is defined as:

\[ NTF(z) = \frac{(1-z^{-1})^2}{D(z)} \]  

Finally, the denominator, \( D(z) \) can be expressed as:

\[ D(z) = (1 - z^{-1})^2 + a_1 b z^{-1}(1 - z^{-1}) + a_2 a_2 z^{-2} \]  

CONCLUSIONS

From this study, it is found that:

- A first-order complex bandpass ΔΣD/A modulator has one pole between \(-f_s/2 \) to \( f_s/2 \).
- A first-order real bandpass ΔΣD/A modulator has two poles between \(-f_s/2 \) to \( f_s/2 \).
- A first-order complex multi-bandpass ΔΣD/A modulator has \( n \) poles between \(-f_s/2 \) to \( f_s/2 \).

From the simulation results, it shows that a complex bandpass ΔΣD/A modulators has better performance in terms of in-band noise and wide bandwidth compared to real bandpass ones. Thus, it proves that a complex bandpass ΔΣD/A modulators would be a more suitable architecture for I-Q signal generation, while multi-bandpass is suitable for multi-tone I-Q signal generation.

Then for a given OSR, complex bandpass has the best SNR, followed by the real bandpass and lastly, \( n \)-bandpass one (\( n \geq 2 \)). Clarification of these relationships with analytical equations would be an interesting future work.

REFERENCES


