How anti-aliasing filter design techniques improve active RF converter front ends

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Introduction

Active analog-to-digital (ADC) front ends using a fully differential amplifier (FDA) can offer a host of advantages, such as better impedance matching, pass-band flatness and signal gain. However, if you require only a portion of the ADC's band for your next design, it might be necessary to use an anti-aliasing filter (AAF) between the output of the FDA and the input of the ADC. An AAF will yield better signal-to-noise (SNR) performance and lower spurious or spurious-free dynamic range (SFDR) within your frequency band requirements.

With any kind of AAF filter constructions, you will have several trade-offs to consider during the implementation process: filter order and topology, or whether you will need back termination or series resistances to enhance the interface between the FDA and the ADC. In this paper, I'll discuss these AAF nuances and how to circumvent any huddles you might encounter in your next design.

AAF design approach

Assuming that you have decided on the correct FDA for your application and whether to use either a low-pass or band-pass filter in order to achieve optimum performance (bandwidth, SNR and SFDR) in front of the ADC, follow these three steps:

1. Understand the amplifier's characterized load impedance (RL). In order for the amplifier to perform at its best, the amplifier should "see" the correct DC load or RL listed in the data sheet for optimum performance. This is the characterized impedance typically found at the top of the specification tables.
2. Determine a starting point for the correct amount of output series resistance to use closest to the amplifier's outputs. This helps prevent unwanted peaking in the pass band. You'll also typically find this information in the FDA's data sheet - **LMH5401 8-GHz, Low-Noise, Low-Power, Fully-Differential Amplifier Data Sheet**.
3. Determine whether to use one or more external parallel resistors to back-terminate the input to the ADC, and the starting value of the input series resistance to isolate the ADC from the filter. These series resistors also help reduce unnecessary peaking in the pass band and "kickback" commonly found in unbuffered ADCs.

Figure 1 shows an example of the specification table.

LMH5401

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6.5 Electrical Characteristics: V_S = 5 V

at T_A = 25°C, VS+ = 2.5 V, VS– = –2.5 V, V_{CM} = 0 V, R_L = 200-Ω differential, G = 12 dB (4 V/V), single-ended input, differential output, and R_S = 50 Ω, (unless otherwise noted)(1)

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT	TEST LEVEL(2)
AC PERFORMANCE							
GBP	Gain bandwidth product	G = 30 dB (32 V/V)		8		GHz	C
SSBW	Small-signal, –3-dB bandwidth	V_O = 200 mV_{PP}		6.2		GHz	C
LSBW	Large-signal, –3-dB bandwidth	V_O = 2 V_{PP}		4.8		GHz	C
	Bandwidth for 0.1-dB flatness	V_O = 2 V_{PP}		800		MHz	C

Figure 1. *Electrical specification table excerpt from the LMH5401 data sheet, where RL = 200Ω.*

The generalized circuit shown in **Figure 2** and filter parameter list in **Table 1** apply to most high-speed differential FDA and ADC interfaces; you can use both as a basis for the AAF design.

Although not every filter construction will be exactly the same, **Figure 2** can serve as a blueprint on how to kick-start your design. Using this design approach will tend to minimize the insertion loss of the filter by taking advantage of the relatively high input impedance of most high-speed ADCs and the relatively low output impedance of the driving source (the FDA).

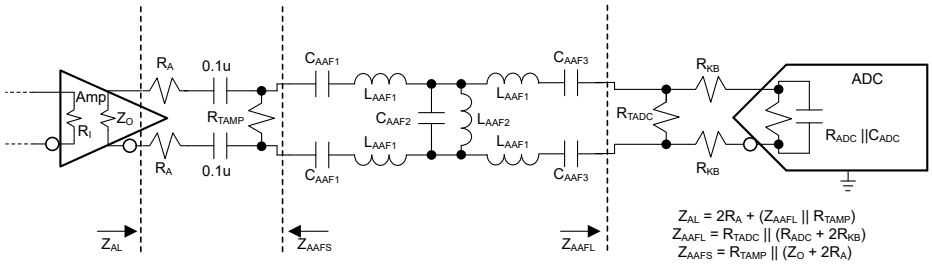

Figure 2. *Generalized FDA and ADC interface with a band-pass filter.*

Symbol	Parameter description
R_i	Amplifier input impedance
Z_o	Amplifier output impedance
R_A	Series output resistance located near the amplifier's outputs
R_{TAMP}	Back-termination resistance near the amplifier outputs
C_{AAF1}	First AAF capacitor
L_{AAF1}	First AAF inductor
C_{AAF2}	Second AAF capacitor
L_{AAF2}	Second AAF inductor
C_{AAF3}	Third AAF capacitor
R_{TADC}	Back-termination resistance near the ADC inputs
R_{KB}	Series kickback resistor located near the ADC's inputs
Z_{AL}	Aggregate load impedance as seen by the amplifier
Z_{AAFS}	Aggregate source impedance of the AAF
Z_{AARL}	Aggregate load impedance of the AAF

Table 1. *Filter parameter definitions.*

AAF design process and parameters

The basic AAF design process and guidelines are:

1. Set the external ADC termination resistor (R_{TADC}) appropriately. This helps the AAF realize a "real" impedance over its desired frequency response.
2. Select R_{KB} based on experience or the ADC data sheet recommendations; typically, this will be between 5Ω and 50Ω.
3. Use **Equation 1** to calculate the filter load impedance so that the aggregate parallel and series combination of R_{TADC}, R_{KB} and R_{ADC} is between 100Ω and 400Ω. See my recommendation in the previous section.

$$Z_{AAFL} - R_{TADC} \parallel (R_{ADC} + 2R_{KB}) \quad (1)$$

4. Select the amplifier external series resistor (R_A). This is typically between 5Ω and 50Ω. R_A helps dampen the amplifier output response and reduce unnecessary peaking in the pass band.
5. Use the calculated Z_{AAFL} so that the total load seen by the amplifier (Z_{AL}) is optimal for the particular differential amplifier chosen. See Step No. 1 above in the AAF Design Approach Section and use **Equation 2**:

$$Z_{AL} = 2R_A + Z_{AAFL} \quad (2)$$

   Keep in mind that ZAL is the FDA's characterized $_{RL}$; therefore, using too high or too low a value can have an adverse effect on the amplifier's linearity.
6. Calculate the filter source resistance using **Equation 3**:

$$Z_{AAFS} = Z_O + 2R_A \quad (3)$$

7. Using a filter design program, design the filter using the same source and load impedances, if possible, Z_{AAFS} and Z_{AAFL}. This helps reduce the amount of loss in the filter. Any mismatch between the input/output impedance has a loss of 10*log(input Z/output Z). For example, with an input impedance of 50Ω and an output impedance of 200Ω, the loss of the filter is –6.0dB or 10*log(50/200). Also, using a bandwidth that is about 10% more or higher than the desired bandwidth of the application will ensure that the intended bandwidth is covered per the application, and help overcome any second- and third-order parasitic losses unrealized during the filter implementation process.

   After running a few preliminary simulations, give the circuit a quick review for the following items:
8. The value of $C_{AAF2\ \&\ 3}$ should be sufficiently big relative to C_{ADC}, which minimizes the sensitivity of the filter to variations in C_{ADC}.
9. The ratio of Z_{AAFL} to Z_{AAFS} should not be more than 6-to-7, so that the filter is within the limits of most filter tables and design programs. Ideally, they should be the same to minimize loss, but this is not usually possible.
10. Try to use a value of C_{AAF2} in the few picofarads range to minimize sensitivity to parasitic capacitance and component variations.
11. Inductors L_{AAF1} and L_{AAF2} should be reasonable values and in the nanohenries range.
12. The value of C_{AFF2} and L_{AAF2} should be reasonable values; select these two parameters to optimize the filter's center frequency. Sometimes circuit simulators can make these values too low or too high. To make these values more reasonable, simply ratio these values with better standard-value components that maintain the same resonant frequency.
13. Use 0201 package styles if possible when designing in the gigahertz range to minimize second- and third-order parasitic effects that could disrupt the filter character shape or outline.

In some cases, the filter design program may provide more than one unique solution, especially with higher-order filters. Always choose the solution that uses the most reasonable set of component values. For filter configurations that end with a shunt capacitor, take the ADC's internal input capacitance into consideration as

well. You may need an iteration or two to set the filter pole and ultimate bandwidth correctly.

AAF design trade-offs

The parameters in this interface circuit are very interactive; therefore, it is almost impossible to optimize the circuit for the primary specifications (bandwidth, bandwidth flatness, SNR, SFDR and gain) without small trade-offs. However, you can minimize bandwidth peaking, which often occurs at the tail end of the bandwidth response, by varying R_A, R_{KB}, or both; either can have a net positive or net negative affect on AAF bandwidth performance.

Notice in **Figure 3** how the pass-band peaking is enhanced or flattened as the value of the FDA's output series resistance (R_A) changes (the blue dashed curves). As the value of this resistance decreases, there is more signal peaking, and the amplifier can drive the signal less to fill the ADC's full-scale input range at the cost of the pass-band flatness response near the edge of the AAF frequency response.

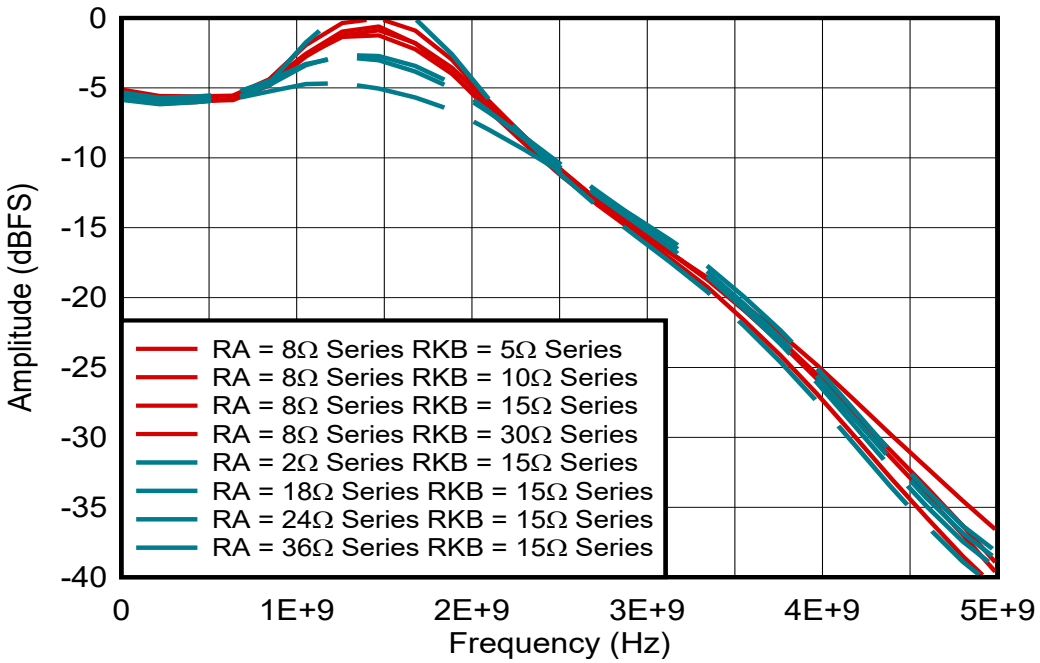

Figure 3. *Pass-band flatness performance vs. RA and RKB variations.*

The value of R_A could also affect SNR performance. Smaller values, while enhancing bandwidth peaking, tend to decrease the SNR because of the increased bandwidth and unwanted noise.

It's also important to select the R_{KB} series resistor on the ADC inputs to minimize distortion caused by any residual charge injection from the internal sampling capacitor within the ADC. However, increasing this resistor also tends to enhance or reduce bandwidth peaking as well, depending on the filter topology.

When optimizing for the AAF's rolloff frequency, varying C_{AAF2} by a small amount allows you to correct for optimal frequency coverage for the application.

Normally, determining the value of the ADC input termination resistor, R_{TADC}, makes the net ADC input impedance look near typical of most amplifier characteristic load (R_L) values. Selecting too high or too low a value for R_{TADC} can have an adverse effect on the amplifier's linearity, which will then be reflected in the overall SFDR signal-chain lineup.

AAF design example

The design example circuit shown in **Figure 4** is a wideband low-pass receiver front end based on the Texas Instruments (TI) **TRF1208**, a 10MHz to 11GHz, 3dB-bandwidth single-ended to differential amplifier and the TI **ADC12DJ5200RF**, a radio frequency (RF) sampling 12-bit dual-channel 5.2GSPS ADC. I optimized the third-order Butterworth AAF based on the performance and interface requirements of the amplifier and ADC; the total insertion loss caused by the filter network and other components was less than 6dB. In this AC-coupled design, the 0.1µF capacitors block the common-mode voltages between the amplifier, its termination resistors, and the ADC inputs.

The 10MHz to 11GHz **TRF1208** differential amplifier accepts a single-ended input and converts it to a differential signal operating at a gain of 16dB to compensate for the insertion loss of the filter network, providing an overall signal gain of +7.8dB.

An input signal of –6.8dBm produces a full-scale 800mV peak-to-peak differential signal at the ADC input.

The overall circuit has a bandwidth of 2.34GHz with a pass-band flatness of <3dB. The SNR and SFDR measured with a 534MHz analog input frequency are 52.5dBFS and 71.4dBFS, respectively. The sampling frequency is 5.2GSPS, thereby creating a wideband low-pass filter covering the entire first Nyquist zone between 10MHz and 2.5GHz. Figure 4 shows the values chosen for the final filter passive components (after adjusting for actual circuit parasitics).

The AAF was designed as a third-order Butterworth filter using a standard filter design program with a differential source impedance (Z_{AAFS}) of 39Ω (2 ´ 18Ω + 3Ω), a differential load impedance of 103Ω (Z_{AAFL}) and a cutoff frequency of 2.4GHz. Because of the higher values of series inductance required in simulation, I decreased these inductors to 3nH in order to account for the inherent trace inductances in the layout and proportionally increased the initial 1.8pF capacitors to ground in the simulations to 2.2pF, thereby helping maintain appropriate rolloff around the 2.4GHz requirement.

The **TRF1208** was not back-terminated in this case in order to achieve net performance, and the net differential impedance load was 139Ω (Z_{AL}). Implementing the 18Ω series resistors isolated the filter capacitance from the amplifier outputs. For further insight on the FDA's impedances, you can**download the S-parameters** .

Installing the 15Ω resistors in series with the ADC inputs isolated the internal switching transients from the filter and the amplifier, as well as providing the necessary characterized loading to the FDA.

I used the ADC's 100Ω input impedance per the data sheet. For further insight on the ADC's impedances, **download the S-parameters**.

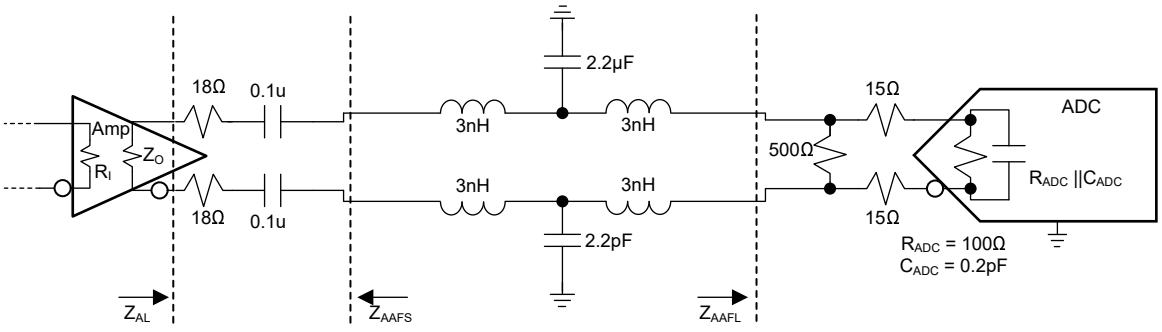

Figure 4. *FDA, AAF, ADC wideband receiver front-end design (simplified schematic).*

Table 2 summarizes the measured performance of the system, where the total insertion loss of the network is approximately 5.8dB.

Performance specs at –1dBFS (FS = 0.8V peak to peak), sample rate = 5.2GSPS, JMODE 3	Final results
Cutoff frequency	2,340MHz
Pass-band flatness (10MHz-2.2GHz)	<3.0dB
SNR full scale at 534MHz	52.5dBFS
SFDR at 534MHz	71.4dBFS
H2/H3 at 534MHz	–71.4dBFS/–73.0dBFS
Overall gain at 534MHz	+7.8dB
Input drive at 534MHz	-12.8dBm (–6dBFS)

Table 2. *Measured performance of the circuit.*

Figure 5 shows the resulting combined FDA, AAF and ADC signal chain's frequency response.

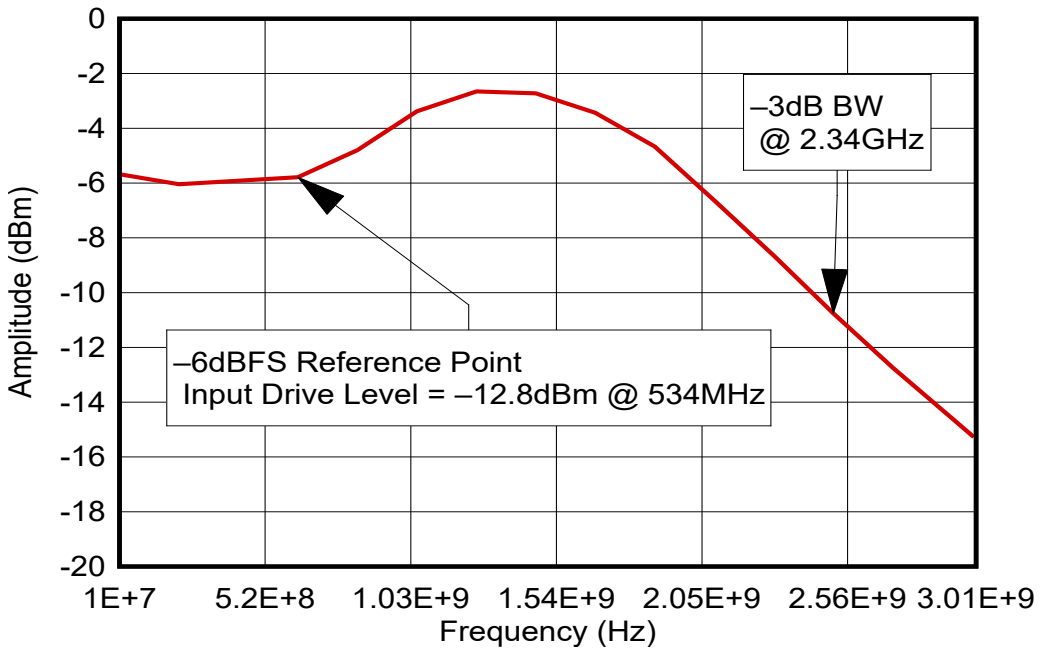

Figure 5. *Pass-band flatness performance vs. frequency.*

Figure 6 shows the SNR and SFDR performance versus frequency, respectively.

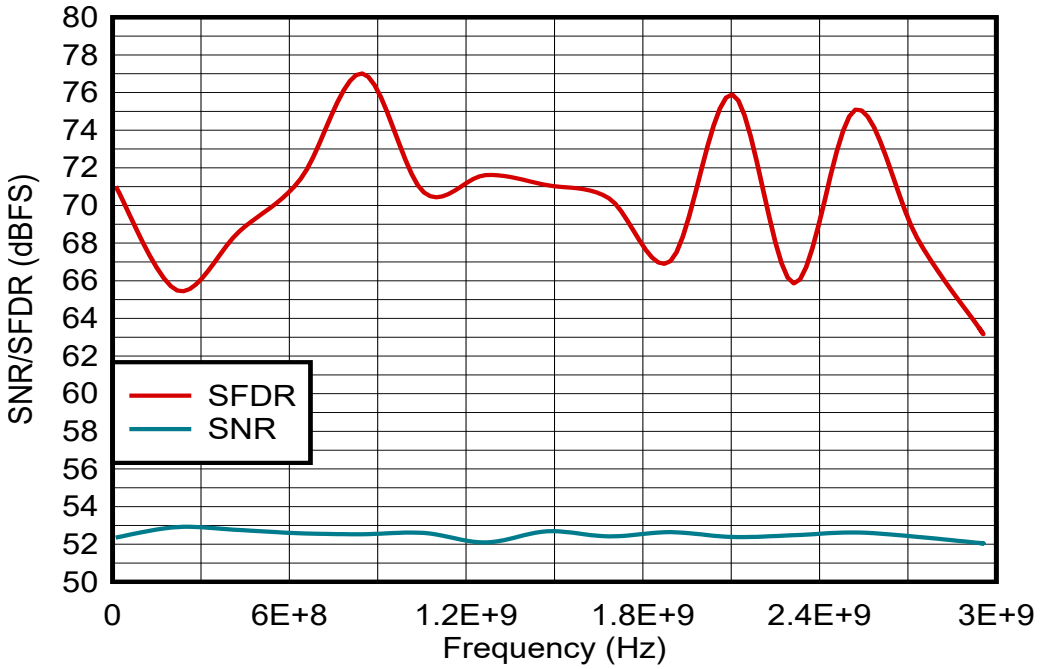

Figure 6. *SNR/SFDR performance vs. frequency, sample rate = 5.2GSPS.*

AAF design conclusion

Understanding all of the different factors, parameters and trade-offs involved in designing an AAF between an FDA and RF ADC can be more difficult than it seems. The design example described in this article gives each parameter equal weight; therefore, the values chosen represent the interface performance for all of the design characteristics. In some designs, you may choose different values to optimize SFDR, SNR or input drive level depending on system requirements. Keep all of these necessary points in mind so that your next AAF doesn't go resonant.

Additional resources

1. Keysight ADS Simulation Software: **https://www.keysight.com/us/en/products/software/pathwave-design-software/pathwave-advanced-design-system.html**.
2. Ansys/Nuhertz Technologies, Filter Solutions Design Program: **https://www.ansys.com/products/electronics/ansys-nuhertz-filtersolutions**.
3. Reeder, Rob. 2022. "**Evaluating high-speed RF converter front-end architectures**." Planet Analog, April 7, 2022.
4. Reeder, Rob. 2022. "**A close look at active vs. passive RF converter front-ends**." Planet Analog, January 24, 2022.
5. Bowick, Chris. 1997. "RF Circuit Design." Boston, Massachusetts: Newnes.

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