

Common Design Challenges and Proper Use of Fully Differential Amplifiers (FDA)

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ABSTRACT

The purpose of this application note is to present the features of the FDA class of amplifiers and discuss ways to optimize their performance. Common errors made in the application of FDAs are also discussed to help users gain a better understanding of FDAs and take full advantage of the benefits these devices offer without unnecessary hindrance and development cost. In turn, this may lead to the adoption of the FDA in applications currently addressed by more traditional amplifiers.

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1 Basic Operation

Figure 1, originally from *Fully-Differential Amplifiers (SLOA054)*, shows a simplified diagram of a FDA.

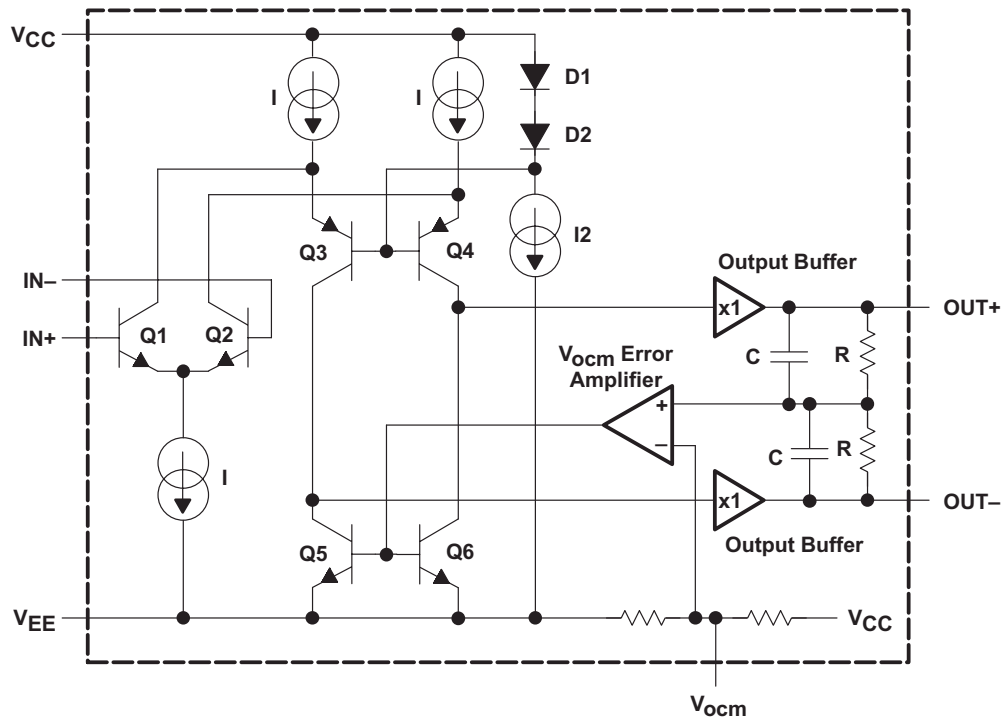


Figure 1. Simplified Diagram of a Fully Differential Amplifier (FDA)

There are many shared attributes between the FDA and the traditional operational amplifier on how the signal flows from the input(s) to the output(s). Taking a closer look at Figure 1, it is easy to identify that the differential signal path consisting of Q1-Q2, followed by Q3-Q6 responds only to a differential input at IN+ and IN- and common-mode inputs are rejected. The Common-Mode path, which does not have an equivalent in the traditional Op Amp, includes the output filtering and the error amplifier. The V_{ocm} Error Amplifier drives the bases of Q5-Q6 to equalize the *average* of the two outputs to the voltage applied to the V_{ocm} input. In many cases, this is the V_{ref} voltage of an ADC which the FDA actively maintains at its output through the servo action of this error amplifier.

2 Finding the Optimal Operating Point by Iteration

One of the design challenges of working with FDAs is the need to set the gain when interfacing to a source which has finite input impedance. The issue is that the same external resistors that set the stage gain also affect the input impedance the source encounters. Many applications require matching, known as *double termination*, and that the stage input impedance value is set precisely in order to avoid reflections and unwanted signal distortion. There are mathematical expressions available that specify the input impedance as a function of the FDA external gain setting resistors, which in turn affects gain. Setting both input impedance and stage gain precisely with the same set of resistors requires patience as it is an iterative process. One method is to use a spreadsheet (see [References \[1\]](#)) to solve for the interacting attributes using iteration. The *Fully Differential Amplifiers Applications: Line Termination, Driving High-Speed ADCs, and Differential Transmission Lines* application note ([SLYT143](#)) shows how to go about computing the value of all external resistors to match the source, get the right gain, and get a balanced design as far as the complimentary inputs are concerned. For a 50-Ω single-ended input that needs the differential gain of 1 V/V from V_s (or 2 V/V from the terminated input), the final result after several iterations is shown in [Figure 2](#).

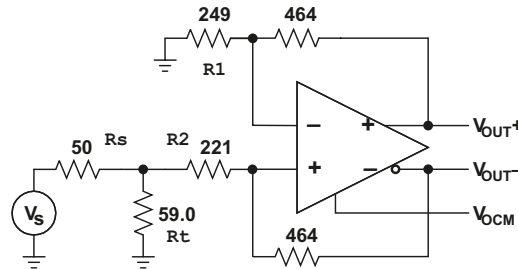


Figure 2. Single-Ended Design After Several Iterations to Compute Component Values

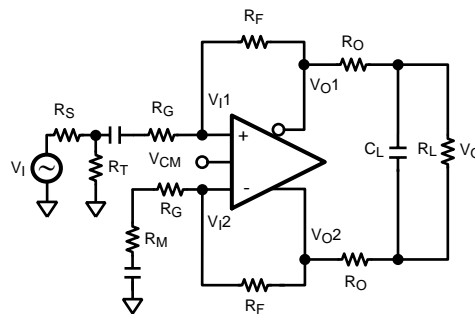
A common error in designing the circuit of Figure 2 is to create an inadvertent imbalance. This imbalance is one where the device complimentary inputs see different impedance. This leads to an unwanted output differential offset. Even if this offset is of little consequence in AC applications, there is yet another ill-effect which has to do with the output distortion created by this asymmetry. In Figure 2, balance is maintained by Equation 1:

$$R1 = R2 + RT \parallel Rs \tag{1}$$

Another issue often encountered with FDAs is the failure to ensure that the input voltage range is not violated. As discussed, the internal CM feedback sets the output CM voltage of each output, but the output voltage is fed back to the input through the external feedback resistors. Depending on the gain, whether or not the circuit is DC or AC coupled, and any CM voltage on the input, the device input voltage levels may encounter CM or signal swing conditions where the FDA input voltage range is exceeded on either end. Simulation tools, such as TINA-TI, do an excellent job of determining the operating conditions of the FDA including the effect of signal swing. Most TI FDA devices have their TINA-TI Macromodel built into the tool which can be utilized effectively to ensure the device operating condition complies with the data sheet specifications.

3 DC Coupled Single-Supply Operation

For many applications, cost can be lowered and reliability can be improved by eliminating the need for a negative supply. However, many analog building blocks require the negative supply for biasing, swing, and the best signal fidelity. This also applies to many FDA applications which could benefit from having a negative supply available for biasing but have to contend with the added cost. Most FDAs can be run with single supply with the VEE terminal tied to ground, but one must be careful of the operating conditions and biasing which are usually exacerbated with single-supply operation. To get around some of the inevitable issues, the solution in many cases is an AC-coupled setup, such as the one shown in Figure 3.



$$*V_{CM} = \frac{V_{O1} + V_{O2}}{2} \quad *BY\ DESIGN$$

$$V_{ICM} = V_{OCM}$$

$$V_{ICM} = \frac{V_{I1} + V_{I2}}{2}$$

Figure 3. Example of AC-Coupled FDA Using Single Supply

Though functional, the circuit of [Figure 3](#) suffers from the additional cost of the capacitors needed to allow single supply operation. It is possible to enhance single-supply operation without the AC-coupling capacitors. This application note on using FDAs for video, *Converting Single-Ended Video to Differential Video in Single-Supply Systems (SLYT427)*, develops a few tricks to apply just the right offset to the undriven input in order to eliminate the differential output offset while maintaining balance and input matching, with the active device delivering the required gain. The result is the streamlined schematic in [Figure 4](#) (from the said application note) where there is no output offset and more importantly no costly or unreliable input coupling capacitors.

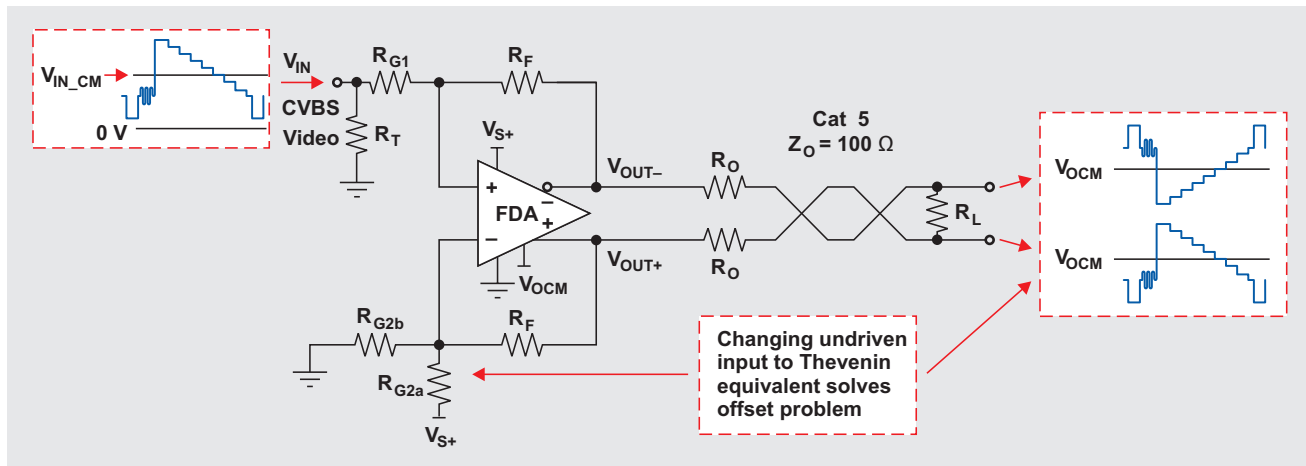


Figure 4. Single-Supply Operation Without the Hassle and Unreliability of Capacitors

4 Output Swing to Ground

FDA devices have an output voltage range which requires certain *headroom* from either supply voltage for normal operation or for lowest distortion. There are rail-to-rail output FDA devices which minimize the required headroom, but even such devices cannot swing closer to ground (or VEE) than 10s to 100s of mill-volt. Certain applications, such as driving high performance low-power ADCs, require the FDA to swing very close to the bottom rail (ground in many cases). These applications can benefit from the use of a Negative Bias Generator. An example of such a device is the LM7705 ([SNVS420](#)) which creates a -0.23-V negative bias voltage from the positive Vcc supply that is available on the board and is used to run the THS4531 ([SLOS358](#)) (RRout) FDA, as shown in [Figure 5](#) and documented in the *Extending Rail-to-Rail Output Range for Fully Differential Amplifiers to Include True Zero Volts* TI Design ([TIDU187](#)), where [Figure 5](#) comes from.

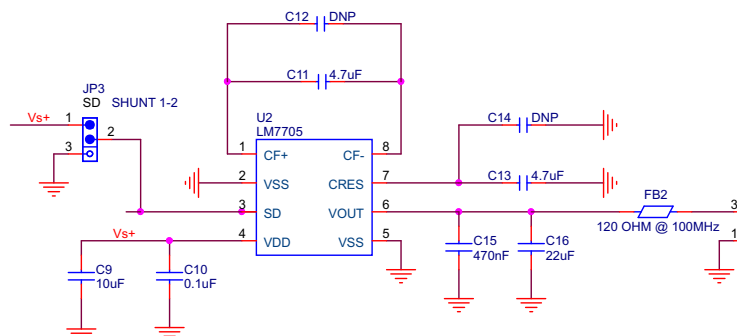


Figure 5. Negative Bias Generated (at Pin 6) Tied to FDA VEE Pin to Allow Output Swing to Ground

There are power conversion products available for creating a negative supply from the positive supply without the complexity and design effort required for a true switching power supply. One such device is the LM2776 ([SNVSA56](#)) which creates the inverted replica of the positive supply with little external circuitry, as shown in [Figure 6](#).

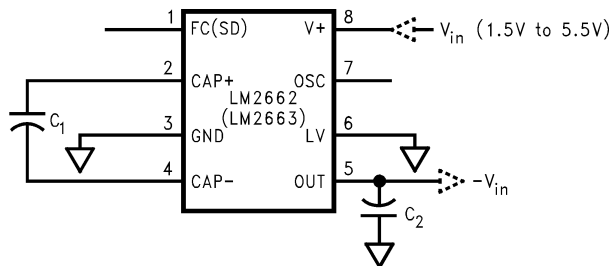


Figure 6. Creating a Negative Bias from a Positive Supply

Regardless of the device chosen for creating the negative bias, it is important to make sure its current handling capability complies with the highest current that has to be supported. This includes any *quiescent* current that the FDA requires in addition to the *load current* that the FDA encounters. The current flowing through the load is supplied by the FDA output transistors, which in turn source that current from the Vcc and the Vee supplies. Therefore, the current handling capability of the negative bias on the VEE pin must include the load current.

5 Differential Cable Driving and Receiving

One of the more intuitive applications of the FDA, due to its complimentary nature, is to drive a twisted pair of cable for video, audio, or similar signals. Sometimes, the signal could be modulated and encoded, as in the case of the HD-CVI (see [References \[2\]](#)). Other times, the signal may be baseband video, an example of which is the ubiquitous application of sending video from an automobile rear-view camera to the driver display using CVBS (composite) video.

In all these applications, the *balanced* nature of the load fits one of the primary advantages of the FDA which is symmetry and internal matching between the complimentary outputs. We are familiar with the positive effect that fully-differential transmission of information has on even order harmonics (see [References \[3\]](#)). Another very important characteristic of differential send and receive is the rejection of the Common-Mode interference which has a better chance of getting attenuated or eliminated at the receive end when compared to a single-ended method.

Once launched onto the transmission medium (a twisted-pair of cables), the video arrives at the far end laden with any interference it might have picked up due to nearby noise sources or the environment. The video receiver is responsible for cancelling the common-mode interference and for pulling out the original differential video out of noise. This requires high Common-Mode Rejection (CMR) not only at DC, but at higher frequencies as well. Unfortunately, this is the region where most amplifiers encounter a roll-off in their rejection characteristics and thus are less effective at rejecting CM AC interference.

All copper transmission lines suffer from high-frequency attenuation which can be remedied with equalization. A typical attenuation profile for CAT5 cable is shown [Figure 7](#). The attenuation (dB) values of [Figure 7](#) for any length L(ft) (see [References \[4\]](#)) is scaled by the factor:

$$\frac{L(\text{ft})}{33(\text{ft})}$$

(for example, 20 dB attenuation at 1 GHz for 66 ft of length) (2)

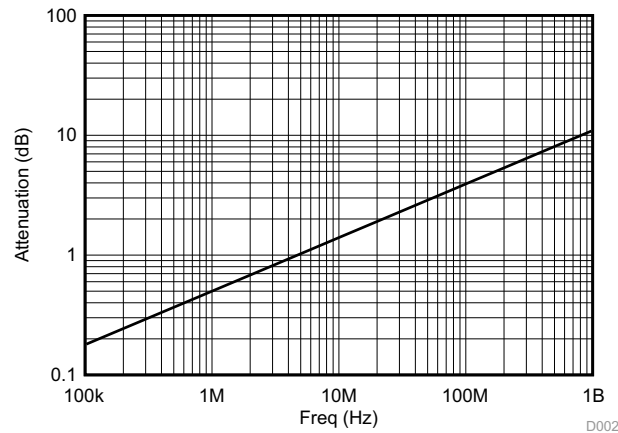


Figure 7. CAT5 Cable (33 ft) Attenuation vs Frequency

Some of the high frequency information that is lost in the transmission at the far-end of the transmission line can be restored by using equalization. The equalizer functions by providing more gain at the high-frequency in order to achieve a flat frequency response in the bandwidth of interest. As shown in [Figure 8](#), this is usually done by careful placement of RC elements (such as R_A and C_A) across the gain setting resistor of the receiver amplifier.

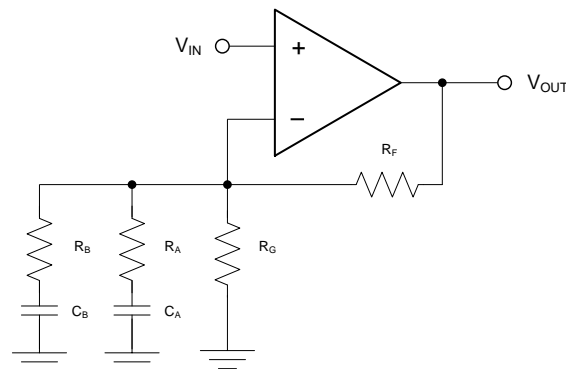


Figure 8. Series RC Elements Across RG Boost Gain at High Frequency

One method that can be taken to design the values of the equalizer components is to follow the approach in the Analog Wire post: *Cable equalization 101 – Automating your design (Part 1)*, see [References \[5\]](#). This method uses a spreadsheet to ease the determination of the interacting poles and zeroes introduced by the RC elements in order to exactly cancel out the known attenuation curve of the transmission line. That is what was done to come up with the schematic shown in [Figure 9](#) for 33 ft of the cable shown in [Figure 7](#).

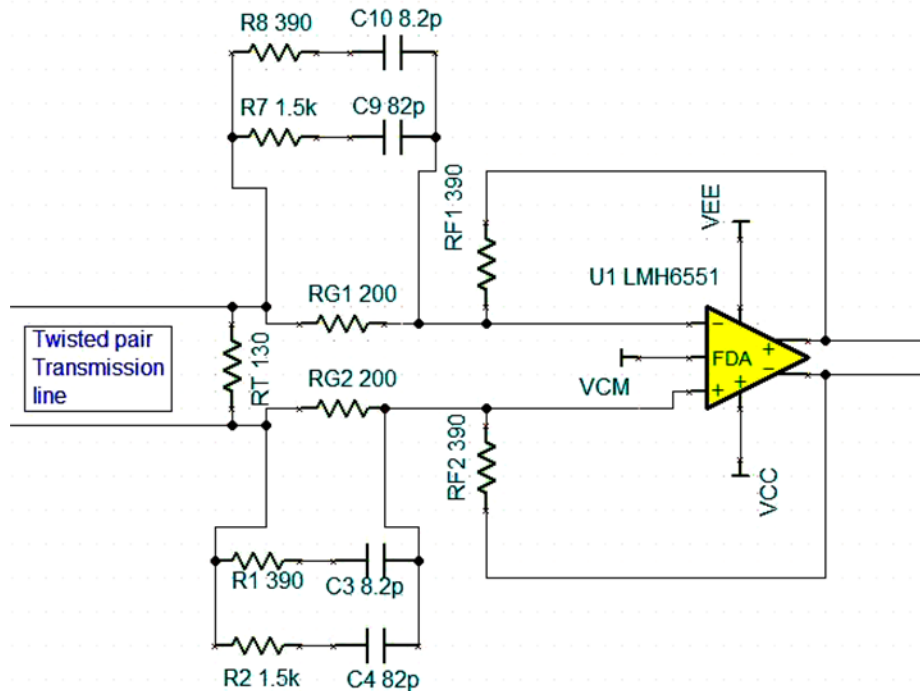


Figure 9. Equalizing CAT5 Cable Receiver

Figure 10 compares the attenuation of the cable with the theoretical gain of the equalizing receiver. The frequency response should be flat up to about 100 MHz due to the fact that the cable attenuation matches the receiver gain.

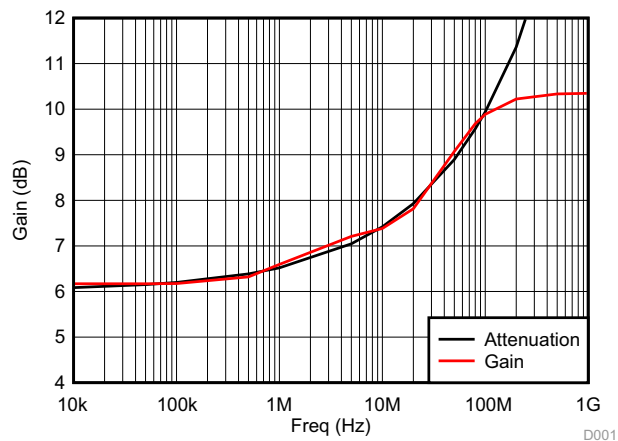


Figure 10. Cable Attenuation vs Receiver Gain

Practical effects, such as finite amplifier bandwidth and other board or component parasitics, limit this theoretical correction to lower frequencies. However, for many audio and video applications, the realizable correction offered by a FDA such as the LMH6551Q-Q1 (SNOSB95), which is also qualified for automotive applications, is more than adequate. Figure 11 shows the measured results of the equalizer compared with the receiver with no equalization when tested with 33 ft of CAT5 cable.

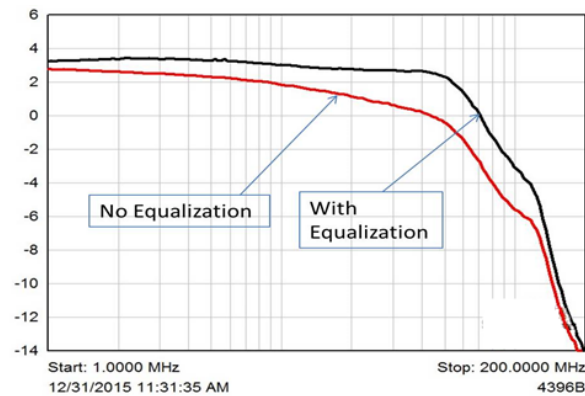


Figure 11. FDA Cable Equalizer Measured Response

Furthermore, the FDA equalizer has some built-in immunity to Common-Mode (CM) noise rejection. Figure 12 shows the measured rejection of CM noise provided by the circuit of Figure 9, when constructed with standard 1% resistor and 10% capacitor values, stays better than 25 dB up to 200 MHz. As expected, the CM rejection of the receiver is relatively high at DC and low frequency and degrades at higher frequencies due to the CMR degradation of the active device.

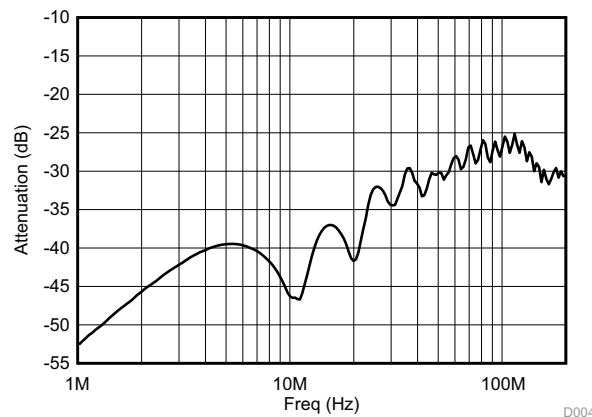


Figure 12. Measured FDA CM Rejection

6 Summary

Practical constraints and realizable capabilities of the FDA devices were enumerated in this writing. Where applicable, some remedies were offered for operational enhancement or to expand the reach of this class of devices so that they may find uses in applications not normally considered. The use of FDA in Automotive video and Infotainment was also discussed and a solution for cable losses was introduced along with measured data showing its performance characteristics.

7 References

1. E2E Support forum which includes spreadsheet for calculating the FDA components: http://e2e.ti.com/support/amplifiers/high_speed_amplifiers/f/10/p/311202/1085553
2. HD-CVI Details: <http://www.embedded.com/print/4402915>
3. Even order harmonics reduction in FDAs (section 6): [SLOA054](#)
4. Cable attenuation characteristics and video standards: http://www.eetimes.com/document.asp?doc_id=1272242
5. *Cable equalization 101 – Automating your design (Part 1)*: https://e2e.ti.com/blogs_/b/analogwire/archive/2013/05/21/cable-equalization-101-automating-your-design

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