

Multiplying DACs—AC/Arbitrary Reference Applications

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INTRODUCTION

A multiplying digital-to-analog converter (DAC) differs from the conventional fixed reference DAC by having the ability to operate with an arbitrary or ac reference signal. This application note details the basic theory behind current output multiplying DACs, and why these DACs are so suitable for ac voltage and arbitrary voltage conditioning.

BASIC WAVEFORM ATTENUATION

A simple method of adjusting the gain of an ac signal is to use the classic inverter op amp stage, choose an amplifier with sufficient bandwidth, and adjust the gain by using the following equation:

$$V_{OUT} = -[RDAC/R_{FB}(V_{IN})]$$

Multiplying DACs offer an ideal building block for multiplying an arbitrary or ac voltage signal. The buffered current output DAC architecture is based on a noninverting gain amplifier structure. A multiplying DAC uses an R-2R architecture to replicate the functionality of the variable RDAC resistor shown in Figure 1. The input impedance to the DAC seen at the V_{REF} pin is fixed, and the output impedance is code dependent to give the equivalent variable RDAC value.

The terms AD55xx and AD54xx used in this application note reference the multiplying DACs listed on www.analog.com/MultiplyingDAC.

FUNCTIONAL BLOCK DIAGRAM

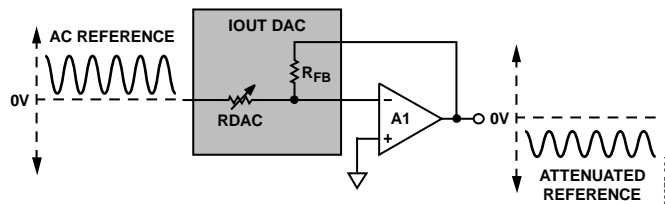


Figure 1. Inverting Gain Configuration

TABLE OF CONTENTS

Introduction	1	Key DAC Specifications for Signal Conditioning	5
Basic Waveform Attenuation	1	Multiplying Bandwidth	5
Functional Block Diagram	1	Analog Total Harmonic Distortion.....	5
Multiplying DACs.....	3	Multiplying Feedthrough Error.....	5
Adding Gain.....	3	Choosing the Correct Op Amp	6
Positive Voltage In/Positive Voltage Out.....	3		
Single-Ended-to-Differential Configuration	4		
Stability Issues	4		

MULTIPLYING DACS

In a multiplying DAC, current is steered to either the virtual ground connected to the IOUT1 node or the ground node (in some parts this is the IOUT2 node), which allows for a very low glitch output voltage (see Figure 2).

One of the key advantages in using an IOUT DAC in this configuration is that the integrated R_{FB} resistor is matched to the RDAC equivalent resistor allowing for very low gain temperature coefficient errors.

When an output amplifier is connected in unipolar mode, as shown in Figure 2, the output voltage is given by

$$V_{OUT} = -\frac{D}{2^n} \times V_{REF}$$

where:

D is the fractional representation of the digital word loaded to the DAC.

- $D = 0$ to 255 (8-bit [AD5450](#)).
- $= 0$ to 1023 (10-bit [AD5451](#)).
- $= 0$ to 4095 (12-bit [AD5452](#)).
- $= 0$ to 16,383 (14-bit [AD5453](#)).
- $= 0$ to 65,536 (16-bit [AD5543](#)).

n is the number of bits.

In brief, the output signal of a multiplying DAC is proportional to the product of the reference input and the digital input number.

ADDING GAIN

In applications where the output voltage must be greater than V_{IN} , gain can be added with an additional external amplifier, or it can be achieved in a single stage.

Increase the gain of the circuit by using the recommended configuration shown in Figure 3. R_1 , R_2 , and R_3 should have similar temperature coefficients, but they must not match the temperature coefficients of the DAC.

POSITIVE VOLTAGE IN/POSITIVE VOLTAGE OUT

To generate a positive voltage output from a multiplying DAC configuration, an extra inverting amplifier can be added to the signal chain to reinvert the output. Another option is to select a part with uncommitted resistors, as shown in Figure 4. The advantage with uncommitted resistors is that they have very similar temperature coefficients.

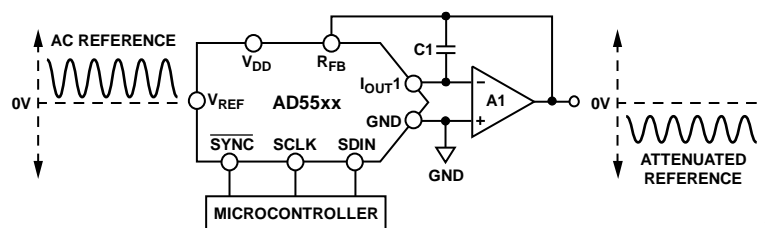


Figure 2. Multiplying DAC, $V_{OUT} = 0V$ to $-V_{REF}$

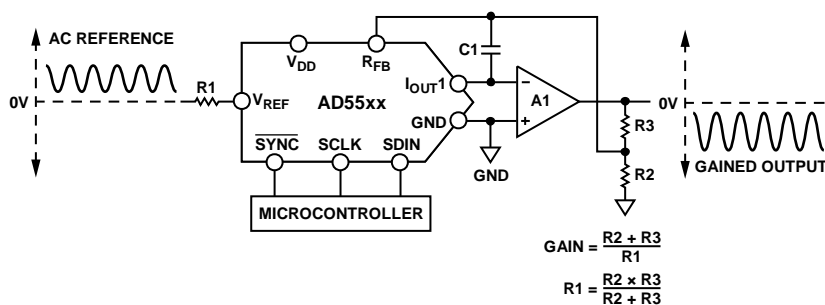


Figure 3. Signal Gain Using Multiplying DACs

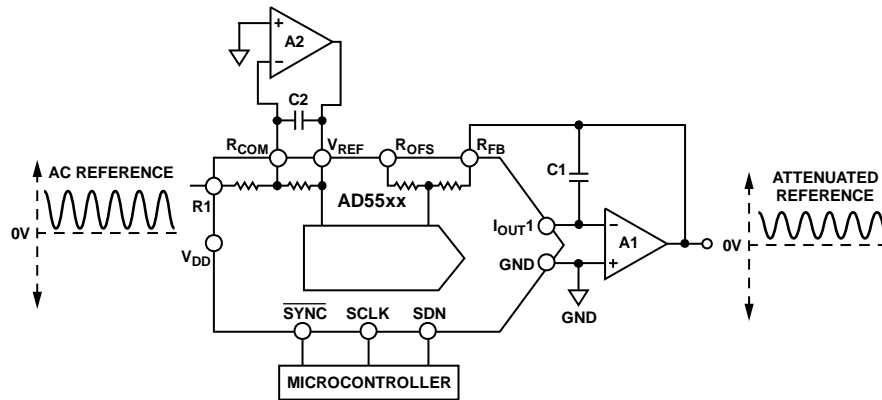


Figure 4. Multiplying DAC, $V_{OUT} = 0\text{ V}$ to V_{REF}

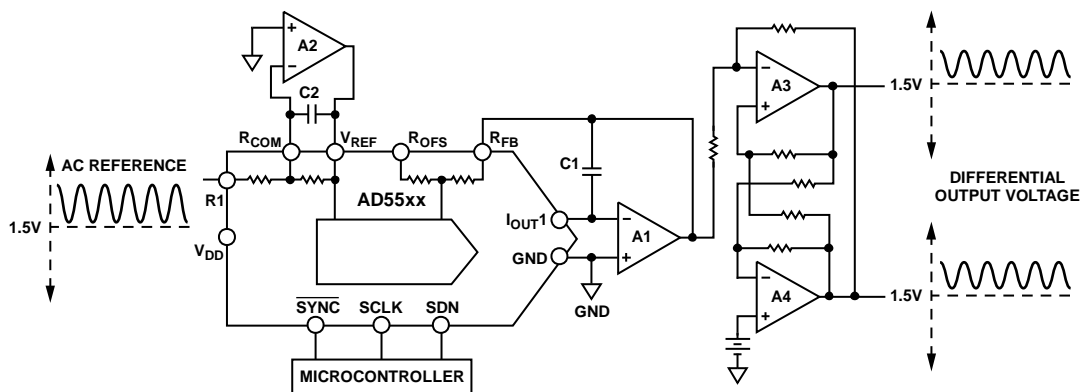


Figure 5. Single-Ended-to-Differential Configuration

SINGLE-ENDED-TO-DIFFERENTIAL CONFIGURATION

To generate a differential output from this configuration, two extra op amps are required. See the [CN-0143](#) Circuit Note, *Single-Ended-to-Differential Converters for Voltage Output and Current Output DACs Using the AD8042 Op Amp*, for detailed information on this.

STABILITY ISSUES

An important component to take into account in achieving the desired waveform conditioning signal is the compensation capacitor. The internal output capacitance of the DAC introduces a pole into the open-loop response that can cause ringing or instability in the closed-loop ramp profiling circuit. To compensate for this, an external feedback capacitor, C1, is usually connected in parallel with the internal R_{FB} of the DAC (see Figure 2). If the value of

C1 is too small, it can produce waveform distortion at the output, and if the value of C1 is too large, it can adversely affect the bandwidth of the system. Because the internal output capacitance of the DAC varies with code, it is difficult to fix a precise value for C1. The value is best approximated according to the following equation:

$$C1 = 20 \sqrt{\frac{C_o}{2\pi \times R_{FB}}} \times \frac{1}{GBW}$$

where:

GBW is the small signal unity-gain bandwidth product of the op amp in use.

C_O is the output capacitance of the DAC.

KEY DAC SPECIFICATIONS FOR SIGNAL CONDITIONING

Some of the key selected ac specifications that must be taken into account when multiplying an ac/arbitrary reference input signal include multiplying bandwidth, analog total harmonic distortion, and multiplying feedthrough error.

MULTIPLYING BANDWIDTH

The multiplying bandwidth is the reference input frequency at which the gain is -3 dB. For a given device, it is a function of amplitude and the choice of compensation capacitance. Figure 6 shows multiplying bandwidth plots for the AD5544, AD5554, or AD545x current output DACs, which can multiply signals up to 12 MHz. The 350 MHz bandwidth of the accompanying low power AD8038 op amp insures that the op amp introduces insignificant dynamic errors on this scale.

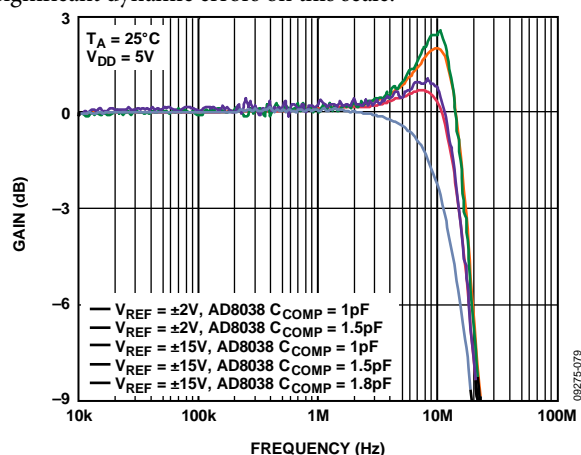


Figure 6. Multiplying Bandwidth

ANALOG TOTAL HARMONIC DISTORTION

Analog total harmonic distortion is a mathematical representation of the harmonic content in the multiplied waveform signal. It is the rms sum of the harmonics (V2, V3, V4, and V5) of the DAC output to the fundamental value, V1, given by

$$THD = 20 \log \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + V_5^2}}{V_1}$$

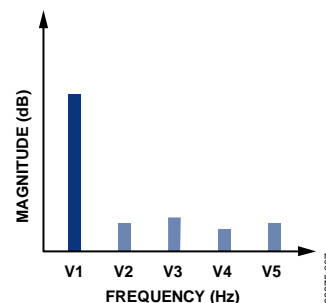


Figure 7. Total Harmonic Distortion

MULTIPLYING FEEDTHROUGH ERROR

The multiplying feedthrough error is defined as the error due to capacitive feedthrough from the reference input to the DAC output when all 0s are loaded to the DAC. Ideally, every time a bit drops 6 dB loss incurs in the gain extending to DB0 (see Figure 8). However, for lower bits, the multiplying feedthrough affects the gain of the part. This is shown in Figure 8 by the flat lines tailing upward for the lower bits. For example, at DB2 for a 14-bit DAC at 1 MHz, it should be 72 dB; however, because of feedthrough, it is actually 66 dB.

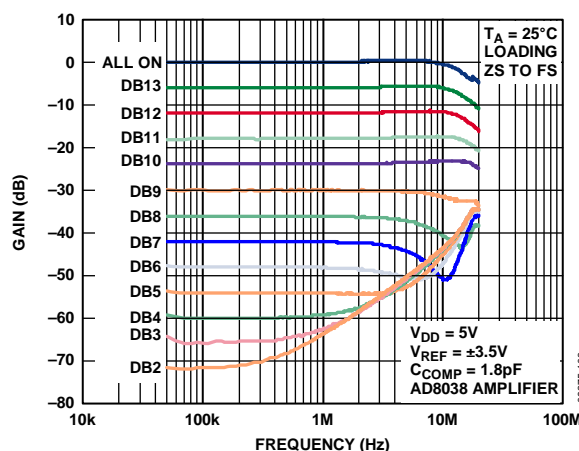


Figure 8. Multiplying Feedthrough Error

CHOOSING THE CORRECT OP AMP

Multiplying DAC circuit performance is strongly dependent on the ability of the selected op amp to maintain the voltage null at the ladder output and perform the current-to-voltage conversion. For best dc accuracy, it is important to select an operational amplifier with low offset voltage and bias current to keep errors commensurate with the resolution of the DAC. Detailed op amp specifications are included in device data sheets.

For applications where the reference input is a relatively high speed signal, a wide bandwidth, high slew rate op amp is required to avoid degrading the signal. The gain bandwidth (GBW) of an op amp circuit is limited by the impedance level of the feedback network and the gain configuration. To determine what GBW is

required, a useful guideline is to select an op amp with a -3 dB bandwidth that is 10 times the frequency of the reference signal.

The slew rate specification of the op amp must be considered to limit distortion of large high frequency signals. For the AD54xx and AD55xx families, an op amp with a slew rate of $100 \text{ V}/\mu\text{s}$ is generally sufficient.

Table 1 provides a selection of operational amplifiers that are useful for multiplying applications.

For additional information, see the multiplying DAC product page at www.analog.com/MultiplyingDAC.

Table 1. Selection of Suitable Analog Devices High Speed Op Amps

Part No.	Supply Voltage (V)	BW @ ACL (MHz)	Slew Rate (V/ μs)	V_{os} (Maximum) (μV)	I_B (Max) (nA)	Packages
AD8065	5 to 24	145	180	1500	0.006	SOIC-8, SOT-23-5
AD8066	5 to 24	145	180	1500	0.006	SOIC-8, MSOP-8
AD8021	5 to 24	490	120	1000	10,500	SOIC-8, MSOP-8
AD8038	3 to 12	350	425	3000	750	SOIC-8, SC70-5, SOT-23-5
ADA4899	5 to 12	600	310	35	100	LFCSP-8, SOIC-8
AD8057	3 to 12	325	850	5000	500	SOT-23-5, SOIC-8
AD8058	3 to 12	325	850	5000	500	SOIC-8, MSOP-8
AD8061	2.7 to 8	320	650	6000	350	SOT-23-5, SOIC-8
AD8062	2.7 to 8	320	650	6000	350	SOIC-8, MSOP-8
AD9631	± 3 to ± 6	320	1300	10,000	7000	SOIC-8, PDIP-8

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