Analog-to-Digital and Digital-to-Analog Converters

<u>Lab Summary</u>: The purpose of the laboratory experiment is to introduce the concepts associated with the conversion of an analog signal to a digital signal and then to convert the digital signal back to analog by utilizing an analog-to-digital converter (ADC) and a digital-to-analog converter (DAC). Calculations will be made on the circuits constructed from readily available components. At the completion of the laboratory experiment, the student shall develop a written report of their finding associated with the converter circuits they investigated and the testing utilized in the WRE Data Conversion Part 1 and 2 Modules.

<u>Lab Goal</u>: The goal of this experiment is to take what you learned and observed in the Digital-to-Analog and Analog-to-Digital labs to make more elaborate measurements of the ADC specifications and to observe the Nyquist theorem in action. This will include the operation of an analog-to-digital and digital-to-analog converter circuit to see the affect of sampling rates as related to the Nyquist theorem and the calculation or measurement of dynamic range, number of bit resolution, signal to noise ratio, effective number of bits, and the spurious free dynamic range.

Learning Objectives

1. Construct an ADC to DAC converter circuit with externally controllable clock frequency.
2. Describe the function and operation of each major component of the circuit.
3. Measure the DC input voltage to the ADC for various digital output signals and the value of DC output voltage from the DAC.
4. Measure the ADC parameters against the primary specifications for the device.

<u>Grading Criteria</u>: Your lab grade will be determined by your performance on the experiment, the lab questions, and the content and quality of your laboratory report.

<u>Time Required</u>: 2 to 4 hours

Equipment and Materials

Part	Quantity
Equipment:	
DC Power Supply 15 volt	2
DC Power Supply 5 volt	1
Digital Multimeter to measure DC voltage	1
Oscilloscope 50 MHz with FFT capabilities	1
Electronic Trainer or breadboard	1
Audio Frequency Spectrum Analyzer (Recommended but not required)	
Components:	
Hookup Wire	As required
SPST Switch	1
1.3 kΩ Fixed Resistor	8
2.2 kΩ Fixed Resistor	1
5 kΩ Fixed Resistor	2
10 kΩ Fixed Resistor	6
20 kΩ Fixed Resistor	1
10 kΩ Variable Resistor (preferably multi turn for improved control)	1
25 kΩ Variable Resistor	1
220 µF 100 V_{DC}	1
330 pF 35 V_{DC}	1
0.01 µF 100 V_{DC}	2
0.1 µF 100 V_{DC}	3
10 µF 35 V_{DC} Tantalum	1
LED (any color)	8
1N914 Diode	1
LT1004 2.5 Voltage Reference	1
ADC0804 Analog-to-Digital Converter IC	1
DAC0800 Digital-to-Analog Converter IC	1
555 IC Timer	1

Special Safety Requirements: No serious hazards are involved in this laboratory experiment, but be careful to connect the components with the proper polarity to avoid damaging them.

Lab Preparation

- Read this document completely before you start on this experiment.
- Acquire required test equipment and appropriate test leads.
- Gather all circuit components and the breadboard or electronic trainer.
- Review and print the laboratory experiment procedure that follows.

Introduction

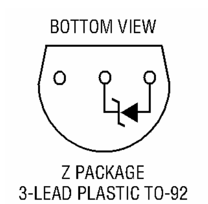
In order to make some of the measurements of the specifications associated with an ADC, the digital output signal must be put into a DAC so the digital signal can be converted back to a voltage for our observation. Demonstrating the Nyquist theorem requires an output signal which can be compared to the input signal. In addition, the measurement of the dynamic range, number of bit resolution, signal to noise ratio, effective number of bits, and the spurious free dynamic range requires an analog voltage as an output.

The first observation we will make is the affect of sample rate as related to the input signal frequency. Next, we will calculate and then measure the dynamic range of the ADC. The measurement of the number of bits of resolution is straight forward and only requires varying the analog input voltage from its minimum to its maximum value and noting the number of digital output bit which change.

The measurement of the signal-to-noise ratio is difficult to measure accurately without the use of a spectrum analyzer or a FFT module in an oscilloscope. We will use an oscilloscope with a FFT module to measure the signal-to-noise ratio by directly reading the values for the output signal and the noise signal amplitudes. The effective number of bits is calculated from the converters signal-to-noise ratio and its total harmonic distortion and requires information from the converters datasheet. The spurious free dynamic range is a measurement of the difference between the RMS value of the desired output signal and the highest amplitude output frequency that is not present as part of the input signal.

This experiment uses the ADC clock signal from a 555 timer circuit which is set to produce a 7.2 kHz square wave with a 50% duty cycle. A function generator supplies the various AC input signals.

The ADC and DAC circuits require an external reference voltage be applied to the $V_{REF}/2$ terminal (9). For this experiment, we will use a LF1004-2.5 voltage reference IC. This IC comes in a three terminal TO-92 package (LF1004CZ-2.5) as shown below.



LF1004-2.5 Voltage Reference IC

Although the symbol used for this IC function is a Zener diode, it actually is a complex circuit, which uses a band gap reference diode.

Lab Procedure

Note: The Circuit schematic, tables, and questions follow the procedure.

1. Use the schematic following this procedure and construct Circuit #1.
2. Perform operational checks and specification measurements to determine if the ADC and DAC are operating within their specifications.
3. Connect the DC voltage input circuit to the ADC V_{in} terminal.
4. Check your circuit one more time for correctness.
5. Energize the DC power supplies. Remember you must energize the op amp before you place an input voltage on its inputs.
6. Measure the voltage $V_{REF}/2$ at the ADC0804 terminal 9 and enter the value. $V_{REF}/2$ = ___________
7. Use the reference voltage to vary the digital output to vary from 00000000_2 to 11111111_2 by varying the analog input voltage from zero to approximately 4.98 V_{DC}. As you vary the analog input voltage from 0 to 5 volts, verify that the digital output signal from the ADC is also varying over the correct binary range.
8. After verifying the binary signal is varying, measure the DAC output voltage. Determine that the voltage varies approximately the same as the input voltage. These simple and quick checks determine the ADC to DAC converter circuit is functioning.
9. Compare the DC input signal to the DC output signal.
   a. Zero the DAC output op amp by adjusting resistor R_A so the op amps output voltage is zero for a binary input to the DAC of 00000000_2.
   b. Complete Table 1 following this procedure by adjusting the input signal to the ADC to produce the output signal shown in the binary output column.
   c. Measure the DAC output voltage at the op amp output and record it in the output voltage column.
10. Connect the AC input circuit in place of the DC input circuit.
11. Set the function generator to a frequency of 1 kHz.
12. Connect a two channel oscilloscope to the input and output terminals of the converter circuit.
    a. Compare the input analog signal to the converter circuit's analog output signal.
       i) With the 555 timer set to produce approximately a 200 kHz clock signal, the output signal is the same frequency and amplitude as the input signal.
       ii) With the input signal frequency, f_i at 1 kHz and the clock frequency, f_S, at 200 kHz the input signal meets the requirement of the Nyquist theorem for the output signal to be at the same frequency as the input.
       iii) Remember the ADC0804 requires a minimum of 64 clock cycles to perform a complete conversion of the input signal.

iv) Therefore the highest frequency we can convert with this circuit without causing aliasing will be:

$$\begin{aligned} f &= \left(f_{CLOCK}/64\right)/2 \\ &= 3406/2 \\ &= 1.7\ \text{kHz} \end{aligned}$$

v) As the frequency of the input signal exceeds 1.7 kHz, aliasing will begin to occur. The output frequency will begin to decrease as you exceed this frequency. The frequency that will appear at the output can be calculated by the following formula:

$$f_a = f_s - f_i$$

Where f_a = Alias frequency
f_s = Sampling frequency
f_i = Input signal frequency

13. Measure the dynamic range of the ADC by determining the ratio of the largest to the smallest possible signal that can be resolved by the ADC.
    a. Input a DC voltage that just causes the LSB to turn off. The binary output will just go from 00000001_2 to 00000000_2. This input voltage is the smallest signal the ADC can resolve.
    b. Input a DC voltage to the input which just causes the binary output to change from 11111110_2 to 11111111_2. This voltage will be the largest possible signal the ADC can resolve.
    c. The dynamic range is given in dB and is calculated using the following formula:

    $$\text{Dynamic Range} = 20\log\frac{V_{\text{largest}}}{V_{\text{smallest}}}$$

    d. It can also be found using the following equation:

    $$\text{Dynamic Range} = 20\log\left(2^N - 1\right)$$

    Where N = Number of bit for the ADC
14. Vary the analog input voltage from its minimum to its maximum value and note the number of digital output bits which changed to determine the number of bits of resolution. Since the ADC0804 has eight bits of binary output and all of them will change for the correct input signal, the bits of resolution equals eight.
15. Use an oscilloscope with a FFT module to measure the signal-to-noise ratio by directly reading the values for the output signal and the noise signal amplitudes.

NOTE: The measurement of the signal-to-noise ratio is easier to measure accurately with the use of a spectrum analyzer. Use one if it is available.

16. Connect the AC input signal circuit to the ADC V_{in} and set the frequency to 1 kHz and 1 V_{RMS}.

17. Connect the probe from the analyzer to the DAC output and set the controls such that the output signal is set for 0 dB.
18. Measure the difference between the signals amplitude and the maximum noise level. The difference between these two values provides the SNR in dB. SNR = _________
19. If an oscilloscope with a FFT or a spectrum analyzer is not available, make this measurement using an oscilloscope.
    a. First, connect the input of the oscilloscope to the DAC output and ground the V_{in} of the ADC to analog ground.
    b. Measure the noise signal as accurately as possible.
    c. Apply the input signal and adjust it for 1 V_{RMS} and 1 kHz.
    d. Measure the output signal and record both readings below:

       V_{noise} = _________

       V_{signal} = _________

    e. Calculate the signal-to-noise ratio using the following formula: SNR = _________

$$\mathrm{SNR} = 20\log\frac{V_{signal}}{V_{noise}}$$

20. Calculate the effective number of bits for the ADC from the converters signal-to-noise ratio and its total harmonic distortion.
    a. This requires information from the converters datasheet or it must be measured using a FFT module or spectrum analyzer.
    b. Using a FFT module, measure the amplitude of the signals fundamental, 2nd, 3rd, 4th, 5th, 6th, and 7th harmonics. Once these measurements are completed, the total harmonic distortion is calculated using the following:

$$\mathrm{THD} = \sqrt{\frac{V_2^2 + V_3^2 + V_4^2 + V_5^2 + V_6^2 + V_7^2}{V_1^2}}$$

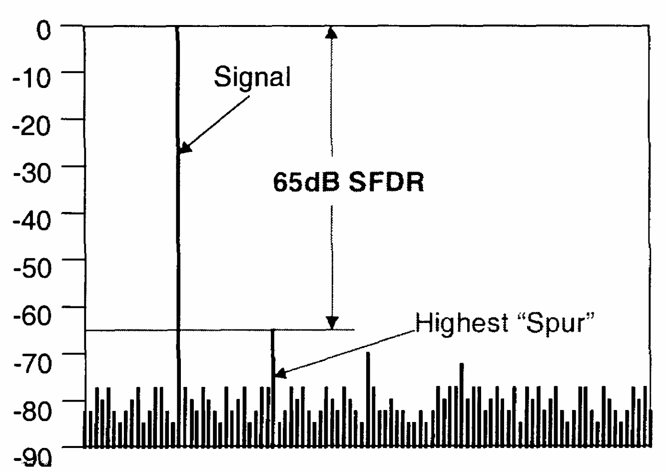
    c. From the SNR and THD measurements, calculate the signal-to-noise and distortion or SINAD for the converter using the following:

$$\mathrm{SINAD} = 20\log\sqrt{10^{-\frac{SNB}{10}} + 10^{\frac{THD}{10}}}$$

    d. Use the following formula to determine the effective number of bits (ENOB):

$$\mathrm{ENOB} = \frac{\mathrm{SINAD} - 1.76}{6.02}$$

21. Determine the spurious free dynamic range of the ADC by measuring the difference between the RMS value of the desired output signal and the highest amplitude output frequency that is not present as part of the input signal.



Spurious Free Dynamic Range

a. Connect the input probe of a FFT module or a spectrum analyzer to the output of the DAC and measure the output.

b. From the display determine the highest amplitude output frequency that is not present in the input and measure the difference between the signal and this "spur". The difference is the spurious free dynamic range of the ADC. Spurious Free Dynamic Range = _____________ dB

Table 1

Input Voltage (DC)	Binary Output ADC	Output Voltage (DC)
	00000000	
	00000010	
	00000100	
	00001000	
	00010000	
	00100000	
	01000000	
	10000000	

Post Lab Questions

1. Why is it important to connect LEDs to the output of the ADC?

2. Why must the ±15 volt supplies be turned on before an input signal is applied to an op amp?

3. What do the results of Table 1 indicate about this ADC to DAC circuit?

4. At what frequency of the input signal did you see aliasing occur? Does that frequency agree with the Nyquist theorem?

5. How are the formulas associated with the calculation of dynamic range related?

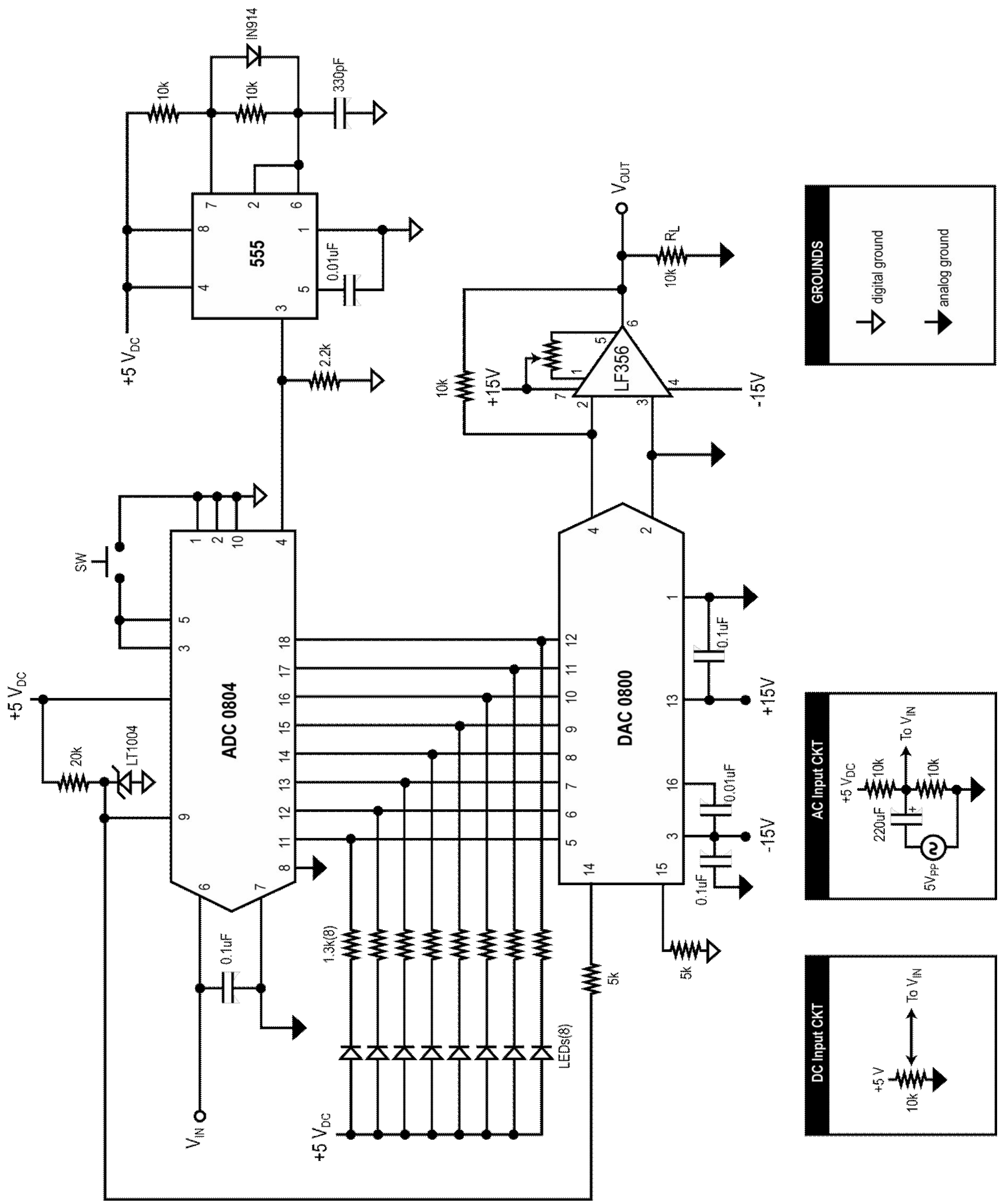
6. How can an eight-bit ADC or DAC have its resolution reduced?

7. How accurate do you think a noise measurement will be using an oscilloscope. How would such a measurement affect a SNR measurement?

8. In the spurious free dynamic range measurement, why is it important to determine the highest spur amplitude that is not present in the input signal?

Written Report: Write a report, which describes the sources of error in each of the measurements made in this lab. Discuss how you could improve these measurements. The length of the report and the format are up to your instructor.

Circuit #1


555
ADC 0804
DAC 0800
LF356
IN914
LT1004
SW
LEDs(8)
1.3k(8)
GROUNDS
digital ground
analog ground
AC Input CKT
DC Input CKT
To V_{IN}
V_{IN}
V_{OUT}
R_L
+5 V_{DC}
+15V
-15V