Laboratory #9
Basics of Digital-to-Analog Converters

I. Objectives

This chapter acquaints you with the other fundamental data converter, which is digital-to-analog converter (DAC). System with ADC and DAC will be also introduced for measuring quantization error.

II. Components and Instruments

1. Components
   (1) OPAMP IC: LM324 ×1
   (2) ADC IC: ADC0804 ×1
   (3) DAC IC: DAC0832 ×1
   (4) Resistors: 10 kΩ ×1, 47 kΩ ×2
   (5) Variable Resistor(R_{VAR}): 10 kΩ ×2
   (6) Capacitors: 150 pF ×1, 0.1 μF ×2, 10μF ×1
   (7) Switch: DIP switch ×1
2. Instruments
   (1) DC power supply (Keysight E36311A)
   (2) Digital multimeter (Keysight 34450A)
   (3) Oscilloscope (Agilent MSOX 2014A)

III. Reading

Section 1.3 of the Textbook "Microelectronic circuits, 6^{th} edition, Sedra/Smith."

IV. Preparation

1. Digital-to-Analog Converter
   (1) Ideal Digital-to-Analog Converter

The block diagram of an N-bit DAC is shown in Fig. 9.1. D is defined to be an N-bit digital input word such that

$$D = \frac{b_1}{2^1} + \frac{b_2}{2^2} + \ldots + \frac{b_N}{2^N}$$

where b_i is bit coefficient that is either 1 or 0. We define b_1 as the most significant bit (MSB) and b_N as the least significant bit (LSB).

The analog output signal, v_O, is related to the digital input code, D, through an analog reference signal, V_{REF}. Here in this lab, we assume both v_O and V_{REF} are voltage signals for simplicity. The relationship between these signals is given by

$$v_O = V_{REF} \cdot \left(\frac{b_1}{2^1} + \frac{b_2}{2^2} + \ldots + \frac{b_N}{2^N} \right) = V_{REF} \cdot D$$

It's useful to define V_{LSB} to be the voltage change when one LSB changes, or, mathematically,

$$V_{LSB} \equiv \frac{V_{REF}}{2^N}$$

Transfer curve of a DAC (2-bit as an example) can be plotted in Fig. 9.2. Concept of V_{LSB} can be also observed in this figure.

For an ideal DAC, the output signals are well-defined values and the maximum value of v_O is not V_{REF} but $V_{REF} \cdot [1-(1/2)^N]$ or equivalently, $V_{REF} - V_{LSB}$.

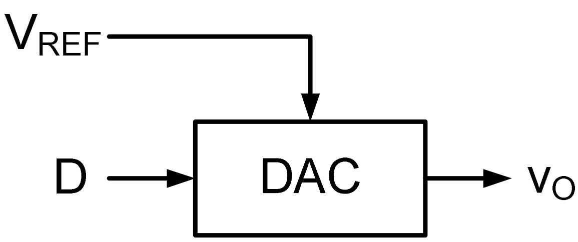

Fig. 9.1 The block diagram of an N-bit DAC

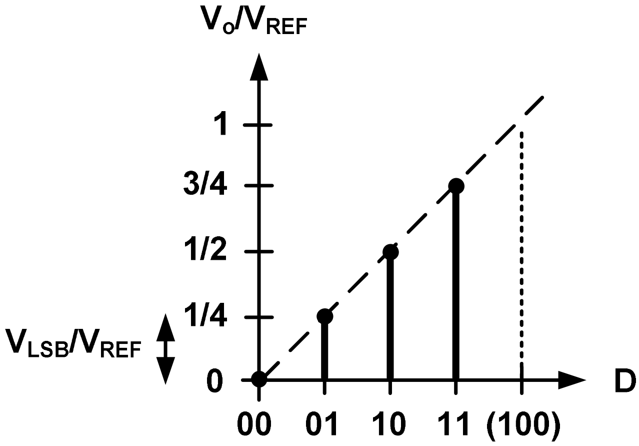

Fig. 9.2 Transfer curve of a 2-bit DAC

(2) An N-bit DAC using a binary-weighted resistive ladder network

Fig. 9.3 shows a simple circuit for an N-bit DAC. The switches S_i are controlled by an N-bit digital input code D. Each switch controls its corresponding current either goes to the ground ($b_i = 0$) or goes to the virtual ground (b_i = 1). Therefore, we have the total current i_O which is given as

$$i_O = \frac{V_{REF} \cdot b_1}{R} + \frac{V_{REF} \cdot b_2}{2R} + \ldots + \frac{V_{REF} \cdot b_N}{2^{N-1} R} \cdot = \frac{2 \cdot V_{REF}}{R} \cdot \left(\frac{b_1}{2^1} + \frac{b_2}{2^2} + \ldots + \frac{b_N}{2^N} \right) = \frac{2 \cdot V_{REF}}{R} \cdot D$$

where the output voltage v_O is given by $v_O = -i_O \cdot R_f = -V_{REF} \cdot D$

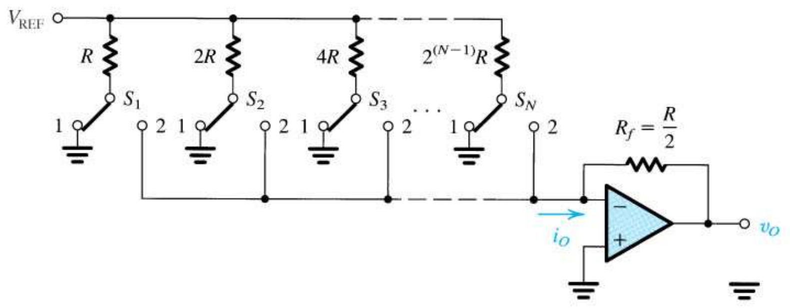

Fig. 9.3 A binary-weighted resistive ladder type N-bit DAC

2. Quantization Error

Quantization error occurs even in ideal ADCs. We can model these errors as being equivalent to an additive noise source and then find the power of this noise source. Consider the setup shown in Fig. 9.4, where both N-bit converters are ideal.

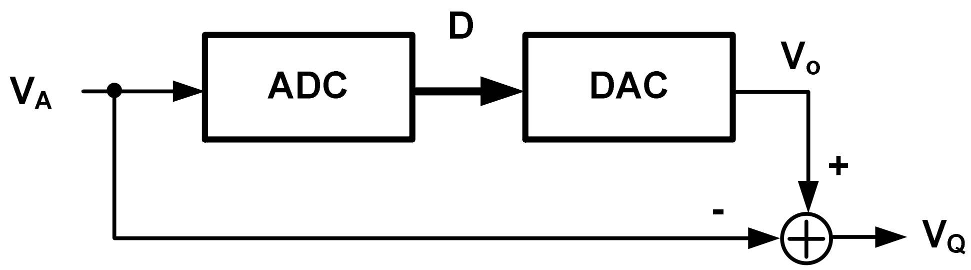

Fig. 9.4 A block diagram to investigate quantization noise

V_A is the input analog signal, D is the corresponded N-bits digital signal of V_A from ADC, and V_o is the analog signal reconstructed by DAC. Taking the difference between original analog signal (V_A) and reconstructed analog signal (V_o), we get the quantization error, V_Q , or mathematically

$$V_Q = V_o - V_A$$

In Fig. 9.4, input signal of ADC, V_A, is a ramp. The output signal from DAC, V_o, appearing as a staircase, is shown in Fig. 9.5. The quantization error will be the difference between V_A and V_o, as shown in Fig. 9.6.

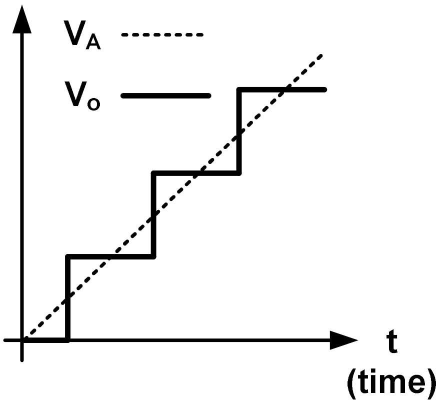

Fig. 9.5 Input signal V_A (ramp) and output signal V_o (staircase)

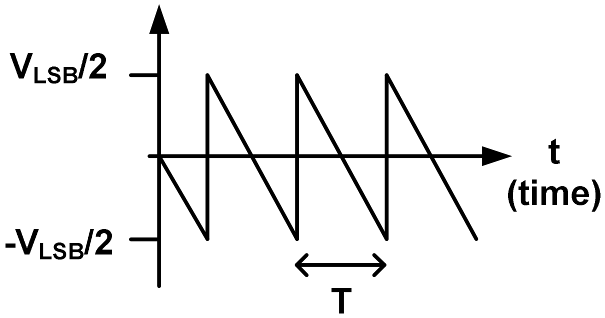

Fig. 9.6 Quantization error V_Q

Note that the quantization error, V_Q, is limited to $\pm\frac{V_{LSB}}{2}$. The average of V_Q is zero, however, the root mean square value of the V_Q, $V_{Q(rms)}$, is given by

$$V_{Q(rms)} = \left[\frac{1}{T}\int_{-T/2}^{T/2} V_Q^2\,dt\right]^{1/2} = \left[\frac{1}{T}\int_{-T/2}^{T/2} V_{LSB}^2\left(-\frac{t}{T}\right)dt\right]^{1/2} = \frac{V_{LSB}}{\sqrt{12}}$$

From above equation, we know that rms value of V_Q, $V_{Q(rms)}$, is proportional to V_{LSB}, thus proportional to the number of bits, N, in the converter.

3. Reference

(1) Adel S. Sedra and Kenneth C. Smith, "Microelectronic circuits, 5th edition, "Oxford University Press, Inc., 2007.
(2) David A. Johns and Ken Martin. "Analog integrated circuit design," John Wiley & Sons, Inc., 1997.
(3) National Semiconductor, Datasheet of DAC0832, "DAC0830/DAC0832 8-Bit

µP Compatible, Double-Buffered Digital-to-Analog Converters," March, 2002.
(4) National Semiconductor, Datasheet of ADC0804, "ADC0801/ADC0802/ADC0803/ADC0804/ADC0805 8-Bit µP Compatible A/D Converters," November, 1999.

4. Pin Information

(1) DAC0832

Datasheet: http://ee-classes.usc.edu/ee459/library/datasheets/DAC0830.pdf

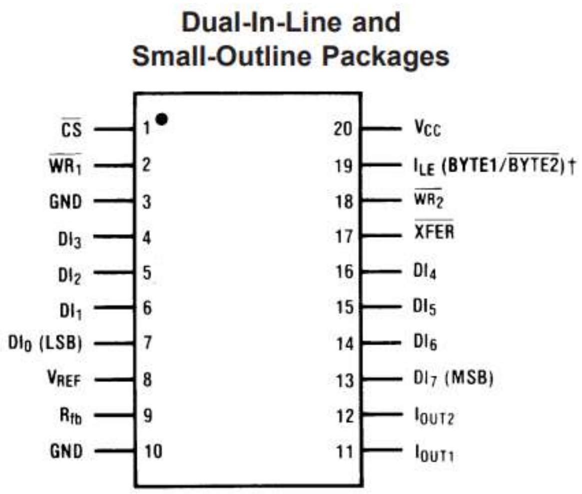

Fig. 9.7 Pin diagram of DAC0832

(2) ADC0804

Datasheet: https://pdf1.alldatasheet.com/datasheet-pdf/view/83230/PHILIPS/ADC0804.html

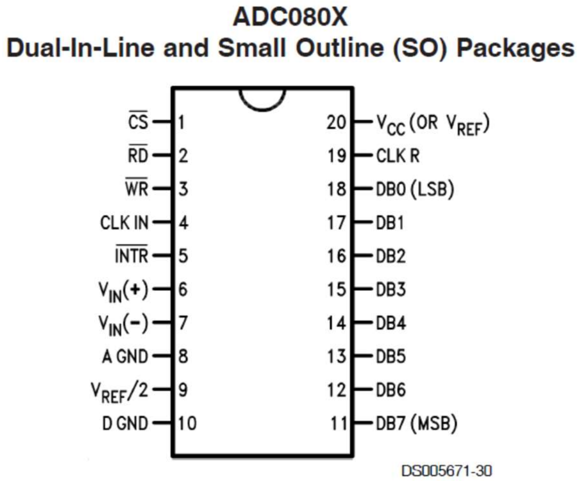

Fig. 9.8 Pin diagram of ADC0804

(3) LM324

Datasheet: https://www.ti.com/lit/ds/symlink/lm324-n.pdf?ts=1595472842932&ref_url=https%253A%252F%252Fwww.google.com%252F

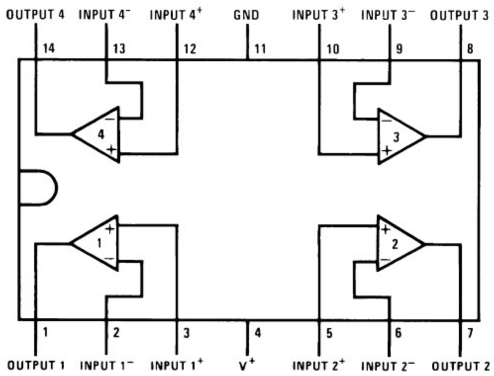

Fig. 9.9 Pin diagram of LM324

V. Explorations

1. DAC0832 output operation

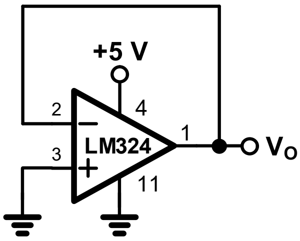

Fig. 9.10 LM324 testing circuit

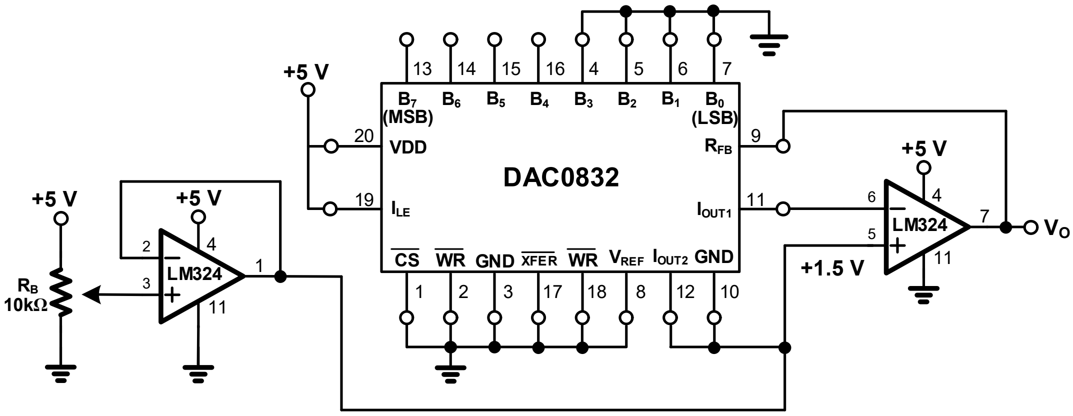

Fig. 9.11

DAC0832 testing circuit

(1) Functional confirmation of LM324

Connect the circuit as shown in Fig. 9.10. After turning the supply ON, make sure that pin4=+5V, pin1=pin2=pin3= pin11=0V. If all pins are at the correct voltage level, then go to the next step.

(2) Circuit setup

Connect the circuit as shown in Fig. 9.11.

(3) Change digital input (B_1 to B_4)

MSB of DAC0832 is pin13 (B_7), and LSB of DAC0832 is pin7 (B_0). Please connect B_0 ~ B_3 to ground. Meanwhile, change digital input (,B_4 ~ B_7) of DAC0832 from 0000 to 1111, and observe analog output (V_O). In this circuit, the logic high value of DAC0832 is +5 V, and the logic low value is 0V.

(4) Finish the Table 9.1

(5) Maintain the DAC testing circuit setup for the 2rd exploration

Table 9.1

Digital input (Binary)	*Analog output V_O (V)*
0001	
0010	
0011	
0100	
0101	
1011	
1100	
1101	
1110	
1111	

2. Quantization error testing circuit for 4-bit operation

   (1) <u>Circuit setup</u>

   Connect the circuit as shown in Fig. 9.12.

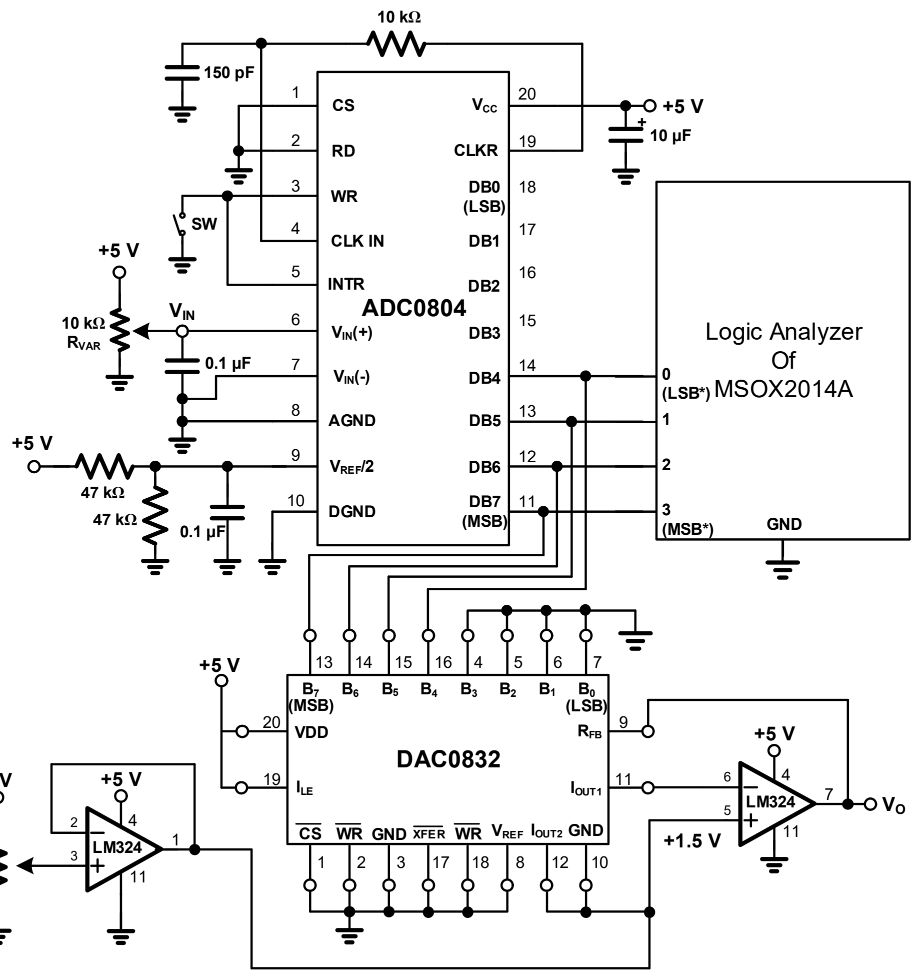

Fig. 9.12 4-bit quantization error testing circuit

(2) Reset the ADC0804

A. Switch on the SW, and set the **CS** and **WR** in logic low value.

B. Switch off the SW, and disconnect the **WR** and **INTR** from **GND**.

(3) Change analog input (V_{IN})

Please use variable resistor(R_{VAR}) to control V_{IN} to corresponding digital output transient of ADC0804 in Table 9.2. Then, go to step4 and record analog output.

(4) Finish the Table 9.2 and Table 9.3

Table 9.2

Analog input V_{IN} (V)	*Digital output (Binary)*	*Analog output V_O (V)*
	0000 → 0001	
	0001 → 0010	
	0010 → 0011	
	0011 → 0100	
	0100 → 0101	
	1010 → 1011	
	1011 → 1100	
	1100 → 1101	
	1101 → 1110	
	1110 → 1111	

Table 9.3

Digital output (Binary)	** Quantization error V_Q (V)*
0000 → 0001	
0001 → 0010	
0010 → 0011	
0011 → 0100	
0100 → 0101	
1010 → 1011	
1011 → 1100	
1100 → 1101	
1101 → 1110	
1110 → 1111	

* Quantization error V_Q formula

$$V_Q = [\frac{(V_{IN} - 0.15)}{V_{LSB,AD}} - \frac{(V_O - 1.5)}{V_{LSB,DAC}}] \times V_{LSB,ADC}$$

Because the V_{LSB} of ADC and DAC are different, V_{IN} and V_O need to be normalized to $V_{LSB,ADC}$ and $V_{LSB,DAC}$ respectively to calculate the quantization error. Additionally, the DC offsets of ADC (0.15V) and DAC(1.5V) need to be subtracted before normalization.

3. DAC0832 negative output operation **(Optional)**

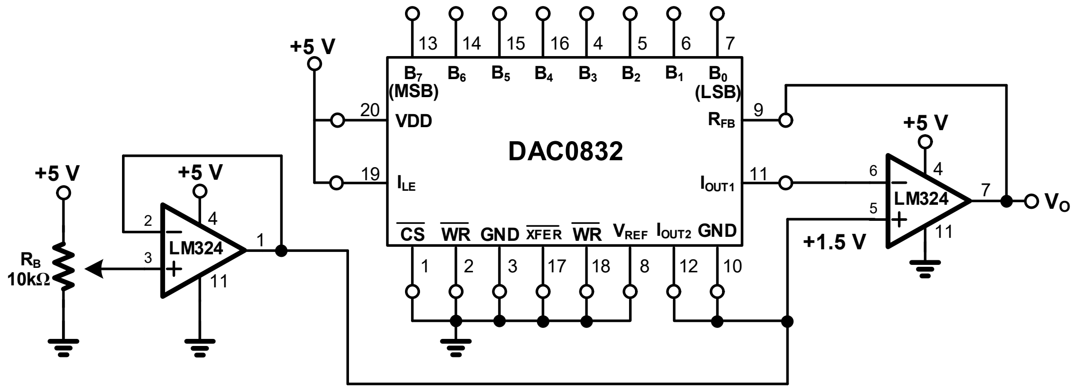

Fig. 9.13 DAC0832 testing circuit

(1) Circuit setup

Connect the circuit as shown in Fig. 9.13.

(2) Change digital input (B_1 to B_8)

MSB of DAC0832 is pin13 (B_7), and LSB of DAC0832 is pin7 (B_0). Please change digital input (B_0 to B_7) of DAC0832 from 0000 0000 to 1111 1111, and observe analog output (V_O). In this circuit, the logic high value of DAC0832 is +5 V, and the logic low value is 0V.

(3) Finish the Table 9.4

Table 9.4

Digital input (Binary)	*Analog output V_O (V)*
0000 0000	
0000 0001	
0000 0010	
0000 0011	
0000 0100	
1111 1011	
1111 1100	
1111 1101	
1111 1110	
1111 1111	

(4) Maintain the DAC testing circuit setup for the 4th exploration

4. Quantization error testing circuit for 8-bit operation **(Optional)**

(1) Circuit setup

Connect the circuit as shown in Fig. 9.14.

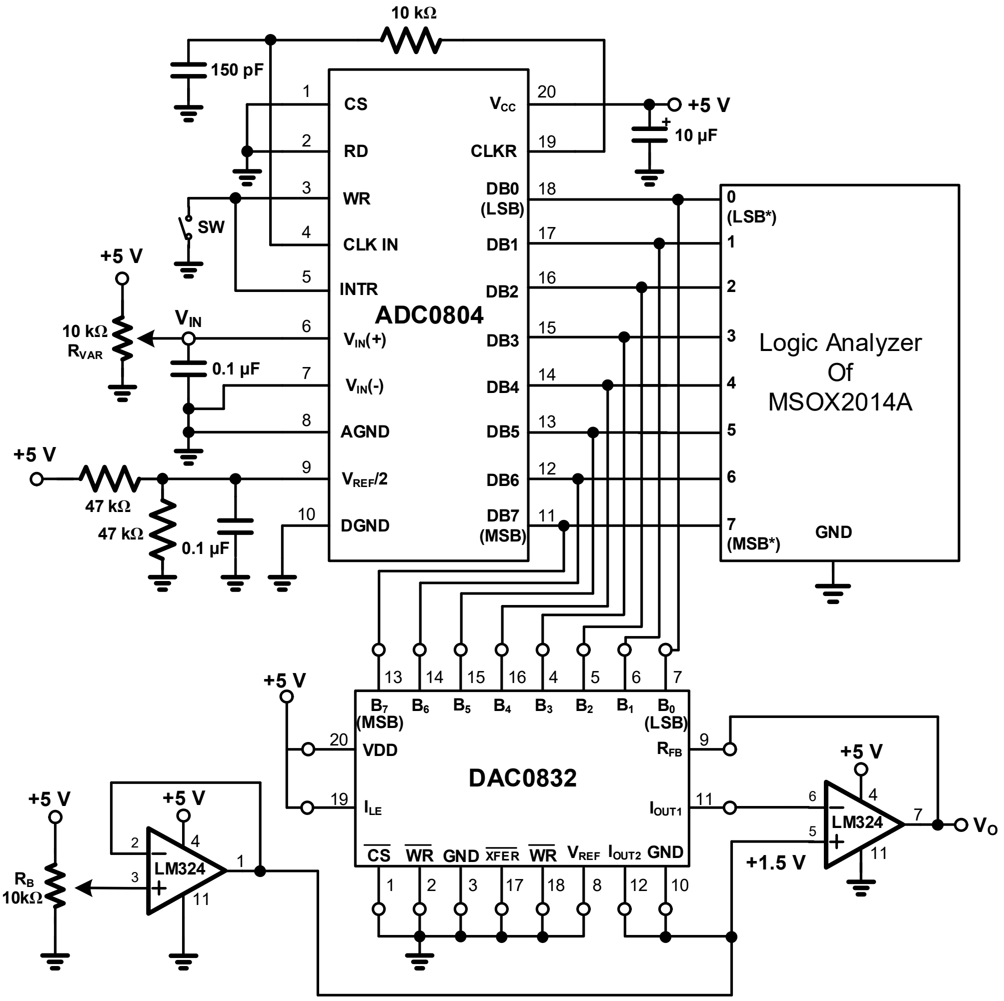

Fig. 9.14 8-bit quantization error testing circuit

(2) Reset the ADC0804

A. Switch on the SW, and set the **CS** and **WR** in logic low value.

B. Switch off the SW, and disconnect the **WR** and **INTR** from **GND**.

(3) Change analog input (V_{IN})

Please use variable resistor(R_{VAR}) to control V_{IN} to corresponding digital output transient of ADC0804 in Table 9.5. Then, go to step4 and record analog output.

(4) Finish the Table 9.5 and Table 9.6

Table 9.5

Analog input V_{IN} (V)	*Digital output (Binary)*	*Analog output V_O (V)*
	0000 0000 → 0000 0001	
	0000 0001 → 0000 0010	
	0000 0010 → 0000 0011	
	0000 0011 → 0000 0100	
	0000 0100 → 0000 0101	
	1111 1010 → 1111 1011	
	1111 1011 → 1111 1100	
	1111 1100 → 1111 1101	
	1111 1101 → 1111 1110	
	1111 1110 → 1111 1111	

Table 9.6

Digital output (Binary)	*Quantization error V_Q (V)*
0000 0000 → 0000 0001	
0000 0001 → 0000 0010	
0000 0010 → 0000 0011	
0000 0011 → 0000 0100	
0000 0100 → 0000 0101	
1111 1010 → 1111 1011	
1111 1011 → 1111 1100	
1111 1100 → 1111 1101	
1111 1101 → 1111 1110	
1111 1110 → 1111 1111	

Laboratory #9 Pre-lab

Class:

Name: Student ID:

1. Please plot the input-output transfer curve for an ideal 2-bit DAC. Use binary code to present the input signal. Normalize the output voltage to reference voltage (V_{REF}).

2. Please briefly describe the pin function of DAC0832. You can find the information from datasheets. In page 9-5, you can find the related links.

Laboratory #9 Report

Class:

Name: Student ID:

1. Exploration 1

Table 9.1

Digital input (Binary)	*Analog output V_O (V)*
0001	
0010	
0011	
0100	
0101	
1011	
1100	
1101	
1110	
1111	

2. Exploration 2

Table 9.2

Analog input V_{IN} (V)	*Digital output (Binary)*	*Analog output V_O (V)*
	0000 → 0001	
	0001 → 0010	
	0010 → 0011	
	0011 → 0100	
	0100 → 0101	
	1010 → 1011	
	1011 → 1100	
	1100 → 1101	
	1101 → 1110	
	1110 → 1111	

Table 9.3

Digital output (Binary)	*Quantization error V_Q (V)*
0000 → 0001	
0001 → 0010	
0010 → 0011	
0011 → 0100	
0100 → 0101	
1010 → 1011	
1011 → 1100	
1100 → 1101	
1101 → 1110	
1110 → 1111	

3. Exploration 3 **(Optional)**

Table 9.4

Digital input (Binary)	*Analog output V_O (V)*
0000 0000	
0000 0001	
0000 0010	
0000 0011	
0000 0100	
1111 1011	
1111 1100	
1111 1101	
1111 1110	
1111 1111	

4. Exploration 4 **(Optional)**

Table 9.5

Analog input V_{IN} (V)	*Digital output (Binary)*	*Analog output V_O (V)*
	0000 0000→0000 0001	
	0000 0001→0000 0010	
	0000 0010→0000 0011	
	0000 0011→0000 0100	
	0000 0100→0000 0101	
	1111 1010→1111 1011	
	1111 1011→1111 1100	
	1111 1100→1111 1101	
	1111 1101→1111 1110	
	1111 1110→1111 1111	

Table 9.6

Digital output (Binary)	*Quantization error V_Q (V)*
0000 0000 → 0000 0001	
0000 0001 → 0000 0010	
0000 0010 → 0000 0011	
0000 0011 → 0000 0100	
0000 0100 → 0000 0101	
1111 1010 → 1111 1011	
1111 1011 → 1111 1100	
1111 1100 → 1111 1101	
1111 1101 → 1111 1110	
1111 1110 → 1111 1111	

5. Problem 1

(1) Please plot the input-output transfer curve according the Table 9.1 by MATLAB or EXCEL. Use decimal code to present input signal. Normalize the output voltage to reference voltage.

(2) Please plot the input-output transfer curve according the Table 9.2 by MATLAB or EXCEL. Use decimal code to present output signal. Normalize the analog input voltage (V_{in}) to reference voltage.

6. Problem 2

Please analyze the measured data in Table 9.3, and explain what ideal values they should be.

7. Conclusion