Precision Digital Sine-Wave Generation with the TMS32010

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Author: Domingo Garcia
Digital Signal Processing – Semiconductor Group

Digital Signal Processing Solutions
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CONTACT INFORMATION

US TMS320 HOTLINE	(281) 274-2320
US TMS320 FAX	(281) 274-2324
US TMS320 BBS	(281) 274-2323
US TMS320 email	dsph@ti.com

Precision Digital Sine-Wave Generation with the TMS32010

Abstract

This report presents two methods of sine-wave generation. The first method is a fast direct table lookup scheme suitable for applications where speech is critical. The second approach, an enhancement of the first, includes linear interpolation to provide higher accurate waveforms.

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INTRODUCTION

Sine-wave generators are fundamental building blocks of signal processing systems which are used in diverse applications, such as communication, instrumentation, and control. In the past, engineers usually designed these oscillators with analog circuitry. Now, however, new high-speed digital signal processors like the TMS32010 present designers with an alternative that in many cases is superior. The TMS32010 provides the speed and accuracy to produce stable, low-distortion sine waves over a wide range of frequencies.

This application report describes two different methods for implementing a digital sine wave generator using the TMS32010. The first method is a fast direct table lookup scheme suitable for applications not requiring extreme accuracy. The second approach, an enhancement of the first, includes linear interpolation to provide sine waveforms with a minimum of harmonic distortion.

DIRECT TABLE LOOKUP METHOD

The first algorithm is a simple, fast table lookup scheme. The sine values for N angles which are uniformly spaced around the unit circle are stored in a table which has the following format:

INDEX	ANGLE	SINE TABLE
0	0 X 360°/N	S[0] = sin(0°/N)
1	1 X 360°/N	S[1] = sin(360°/N)
2	2 X 360°/N	S[2] = sin(720°/N)
.	.	.
.	.	.
.	.	.
N-2	(N-2) X 360°/N	S[N-2] = sin((N-2) X 360°/N)
N-1	(N-1) X 360°/N	S[N-1] = sin((N-1) X 360°/N)

A sine wave is generated by stepping through the table at a constant rate (in effect, moving counterclockwise around the unit circle), wrapping around at the end of the table whenever 360° is exceeded. Using the table index as the angle parameter and DELTA as the step size, this lookup method generates the sequence:

$$S[\text{mod}(k \times \text{DELTA}, N)] \qquad \text{for } k = 1, 2, 3, 4, \ldots$$

where mod(a,b) = remainder of the division a/b when this quotient is computed as an integer [e.g., mod(22.34,5) = 2.34)]

The 'mod' operator provides the wraparound at the end of the table. Figure 1 illustrates this algorithm.

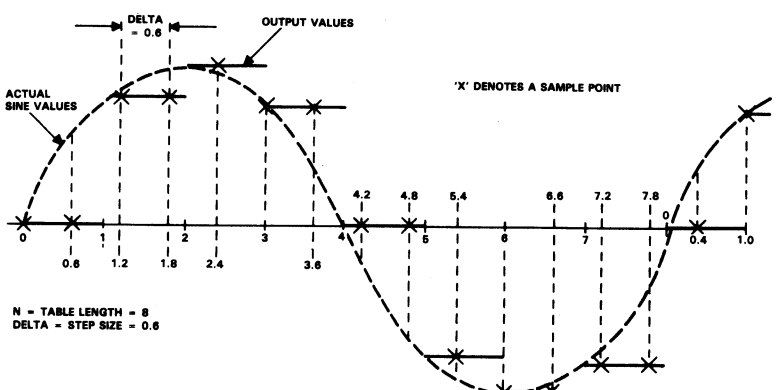

Figure 1. Direct Table Lookup

The sampled waveform generated is only an approximation to a sampled sinusoid. In general, the longer the table is the more resolution it provides, and consequently, the closer the approximation will be.

The frequency, f, of the sine wave depends on two factors:

(1) The time interval between successive samples, i.e., the sampling interval, t

(2) The step size, DELTA

f is given by the equation:

$$f = \frac{DELTA}{t \text{ X } N} \text{ [Hz]} \quad \text{where t is expressed in seconds}$$

Note that to satisfy the Nyquist criterion there must be at least two samples generated each sinusoid period. This requires that DELTA $\leq$ N/2.

In Figure 1, N = 8 and DELTA = 0.6. If, for instance, eight samples are generated each millisecond, then t = 0.000125 seconds and

$$f = \frac{0.6}{8 \text{ X } 0.000125} \text{ Hz} = 600 \text{ Hz}$$

TMS32010 Implementation

This section describes the concise TMS32010 subroutine, given in Appendix B, which implements the table lookup scheme based on a sine table with 128 entries. Each time this subroutine is called, the next sample point is calculated. This subroutine uses:

(1) 138 (=128 + 10) words of program memory space (128 words for sine table storage and 10 words for program memory)
(2) 6 words in data memory as working registers

If this program is used as a subroutine, each sample can be computed in 3.0 microseconds. However, if the code is inserted directly in line with the code of a master program, avoiding the overhead of a subroutine, a sample can be computed in 2.2 microseconds.

The values in the sine table are all scaled. The decimal values, +1.0 and −1.0, are represented by the two's complement hexadecimal values 4000 and C000, respectively. All other values are scaled and rounded to the closest hexadecimal number. Rounding is used, rather than truncation, to avoid adding unnecessary distortion.

The 16-bit data memory location 'ALPHA' serves as a modulo 128 counter which cycles through the sine table to select the sample points. ALPHA is regarded as having an integer and fractional part with the format:

Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0

The 16-bit data memory locaion 'DELTA' contains the step size. DELTA has the same (integer.fraction) format as ALPHA. Every time the sine wave subroutine is called, the contents of ALPHA are incremented by the contents of DELTA. The integer portion of ALPHA (i.e., the eight MSBs) is the pointer to the sine table. However, because the table starts at address location SINE, this pointer is offset by the value for that address before the table is accessed. The eight most significant bits of ALPHA are masked when ALPHA is updated to insure that they never exceed 127. The routine returns the sine value in the data memory location 'SINA'.

For any given sampling interval, t, the frequencies which can be generated must be of the form

$$f = \frac{DELTA}{t \text{ X } 128} \text{ [Hz]} \quad \text{where t is expressed in seconds}$$

Since DELTA has a precision of eight bits to the right of the decimal place, any desired frequency ($\leq$ 1/2t [Hz]) can be approximated with an error of no more than

$$\frac{1/256}{t \text{ X } 128} \text{ [Hz]} = \frac{1}{32768 \text{ X } t} \text{ [Hz]}$$

For example, if the sampling frequency is 8 kHz, then the frequency resolution is

$$\frac{8000}{32768} \text{ Hz} = 0.25 \text{ Hz}$$

Harmonic Distortion

Due to approximations made in calculating the samples of a sine wave of frequency f, a certain amount of the "energy" of the samples' waveform will fall into other frequencies as well. These frequencies are either:

(1) Harmonic frequencies, nf, where n = 2, 3, 4, ..., or
(2) Subharmonic frequencies, nf/m, where n and m are integers.

This spurious energy results in noise which is referred to as "harmonic distortion." It is usually measured in terms of Total Harmonic Distortion (THD) which is defined as the ratio

$$THD = \frac{\text{spurious harmonic energy}}{\text{total energy of the waveform}}$$

There are two sources of error in the table lookup algorithm which cause harmonic distortion:

(1) Quantization error is introduced by representing the sine table values by 16-bit numbers.
(2) Larger errors are introduced when points between table entries are sampled. This occurs when DELTA is not an integer.

The longer the sine table is, the less significant the second error source will be. Consequently, harmonic distortion decreases with increasing table length. Furthermore, when DELTA is an integer, quantization is the only error source, and THD is extremely small regardless of table size. THD is given for several table lengths and values of DELTA in Figure 2. Note that the figures in this table only represent the THD in the digitized sine wave. If the sine wave is reconstructed using a digital-to-analog converter and analog filters, these analog devices will contribute additional distortion. (The procedure for computing THD is described in Appendix A.)

LINEAR INTERPOLATION METHOD

To decrease the harmonic distortion for a given table size, an interpolation scheme can be used to compute the sine values between table entries more accurately. Linear interpolation is the simplest method to implement. This method uses the values of two consecutive table entries as the end points of a line segment. Sample points for parameter values falling between table entries assume values on the line segment between the points. This algorithm is illustrated in Figure 3.

TABLE LENGTH: 32

DELTA	THD
2.0	0.00000024
2.25	0.00300893
2.50	0.00240751
2.75	0.00300917
3.0	0.00000024
8.25	0.00300924
11.625	0.00315807

TABLE LENGTH: 64

DELTA	THD
2.00	0.00000048
2.25	0.00075269
2.50	0.00060219
2.75	0.00075239
3.00	0.00000018
8.25	0.00075204
11.625	0.00079078

TABLE LENGTH: 128

DELTA	THD
2.00	0.00000054
2.25	0.00018859
2.50	0.00015080
2.75	0.00018835
3.00	0.00000012
8.25	0.00018889
11.625	0.00020128

Figure 2. Total Harmonic Distortion Using Direct Table Lookup

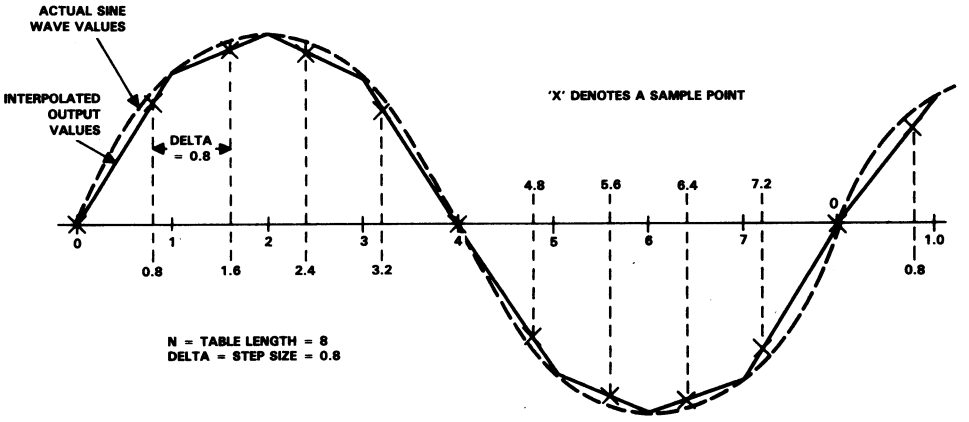

Figure 3. Linear Interpolation

This algorithm is based on the linear approximation

$$\sin(360°(I+D)/N) \cong \sin(360°I/N) + D \times \{\sin(360°(I+1)/N) - \sin(360°I/N)\}$$

$$= S[I] + D \times \{ S[I+1] - S[I] \}$$

where N is the sine table length,
I is an integer such that $0 \leq I \leq N-1$, and
D is a decimal number such that $0 \leq D < 1.0$

The value, $S[I+1] - S[I]$, is the slope of the line segment between the two sample points which bracket the value $I+D$ (i.e., $I \leq I+D < I+1$).

All the values required for this interpolation scheme are stored in the following two tables:

INDEX	ANGLE	SINE TABLE	SLOPE TABLE
0	0 X 360°/N	S[0] = sin(0°/N)	S[1] - S[0]
1	1 X 360°/N	S[1] = sin(360°/N)	S[2] - S[1]
2	2 X 360°/N	S[2] = sin(720°/N)	S[3] - S[2]
.	.	.	.
.	.	.	.
.	.	.	.
N-2	(N-2) X 360°/N	S[N-2] = sin(360°(N-2)/N)	S[N-1] - S[N-2]
N-1	(N-1) X 360°/N	S[N-1] = sin(360°(N-1)/N)	S[0] - S[N-1]

TMS32010 Implementation

The sample TMS32010 implementation of this linear interpolation scheme, given in Appendix C, is an enhancement of the table lookup method. This subroutine is based on 128-entry sine and slope tables. Each time this subroutine is called, the next sample point is calculated. This subroutine uses:

(1) 276 (= 128 + 128 + 20) words of program memory space
    (128 words for sine table storage,
    128 words for slope table storage, and
    20 words for program memory)
(2) 9 words in data memory as working registers

If this program is used as a subroutine, each sample can be computed in 5.4 microseconds. However, if the code is inserted directly in line with the code of a master program, avoiding the overhead of a subroutine, a sample can be computed in only 4.6 microseconds.

Just as in the table lookup algorithm, a sine wave is generated by stepping through the sine table at a constant rate, wrapping around at the end of the table whenever 360° is exceeded. The table index is used as the angle parameter, denoted by ALPHA.

DELTA denotes the step size for this routine also. In this case, however, sample points falling between the samples in the sine table are evaluated using the linear approximation formula given above.

The values in both the sine and slope tables are calculated in the same way as they were for the table lookup program. The decimal values, +1.0 and −1.0, are represented by the two's complement hexadecimal values 4000 and C000, respectively. All hexadecimal values are rounded rather than truncated to the closest 16-bit representations to reduce quantization noise.

Because the method to compute the step size is the same as that used in the table lookup scheme, the frequency resolution will also be the same. However, because of the linear interpolation between table entries, sine values are no longer limited to the values stored in the table. This allows the error between the computed value and the actual value to be less.

Harmonic Distortion

Figure 4 lists the distortion of several sine waves generated using the TMS32010 linear interpolation routine for various table lengths and step sizes. These results clearly show that the distortion for a particular fractional step size decreases if the size of the table is increased just as in the direct table lookup case. However, for the same non-integer step size and the same table length, the distortion for the linear distortion method is much lower than that of direct table lookup.

These values were experimentally determined and the method used to compute them is given in Appendix A.

TABLE LENTH: 32

DELTA	THD
2.0	0.00000024
2.25	0.00169343
2.50	0.00135476
2.75	0.00169379
3.0	0.00000024
8.25	0.00169361
11.625	0.00177808

TABLE LENGTH: 64

DELTA	THD
2.00	0.00000048
2.25	0.00018884
2.50	0.00015055
2.75	0.00018771
3.00	0.00000018
8.25	0.00018806
11.625	0.00019815

TABLE LENGTH: 128

DELTA	THD
2.00	0.00000054
2.25	0.00000054
2.50	0.00000012
2.75	0.00000101
3.00	0.00000012
8.25	0.00000006
11.625	0.00000155

Figure 4. Harmonic Distortion Using Linear Interpolation

IMPLEMENTATION TRADE-OFFS

There are three trade-offs that must be considered when implementing the algorithms described above. They are speed, accuracy, and the size of the table ROM.

The direct table lookup method is the fastest implementation. Using a table that ranges from 0° to 360°, the routine needs only to address the table and compute the next angle. However, the table occupies more program memory space than is absolutely required.

To minimize the amount of program memory required for the sine table, one can take advantage of the symmetry of the sine function. By keeping track of the quadrant as ALPHA is increased, a table that ranges from 0° to 90° will be sufficient. This decreases the size of the table by three-fourths. However, the extra code necessary to keep track of the quadrant will increase the execution time of the routine.

If harmonic distortion is important, then some form of interpolation is needed. One can use the linear interpolation method of the second example or other approximations such as a Taylor Series or Maclaurin Series expansions carried out to the second- or third-order term, or beyond. These schemes will, however, also increase the amount of code as well as the execution time.

APPENDIX A: COMPUTATION OF TOTAL HARMONIC DISTORTION

To determine the Total Harmonic Distortion (THD) of a sampled data sine wave, the amount of energy due to frequency components other than the fundamental is divided by the total energy of the wave. This is computed from the formula:

$$\text{THD} = [\text{E(total)} - \text{E(fundamental)}] \,/\, \text{E(total)}$$

For the most accurate results, these energy terms should be calculated over a full cycle of the signal. In the case of a sine wave generated by either of the two methods, a full cycle may actually consist of several sinusoid periods. For instance, If N = table length = 128 and if DELTA = step size = 1.5, a cycle will only be completed for the smallest n for which n x 1.5 is evenly divisible by 128. This occurs for n = 256 which marks the end of the second sinusoid period.

In general, if DELTA = A/B where A and B are relatively prime integers, and N = table length, then the sequence x(n), n = 1,2,3, ... of sine-wave samples will cycle after no more than B x N points.

The amount of total "energy" in a cycle of this length is

$$\text{E(total)} = \sum_{n=0}^{BN-1} x^2(n)$$

The amount of "energy" in the fundamental frequency over this period is

$$\begin{aligned} \text{E(fundamental)} &= 1/BN\ (|X(A)|^2 + |X(BN-A)|^2) \\ &= 2/BN\ |X(A)|^2 \quad \text{for a real sequence} \end{aligned}$$

where the X(k) terms are terms of the Discrete Fourier Transform defined by the equation

$$X(k) = \sum_{n=0}^{BN-1} x(n)\exp(-j(2\pi/N)nk)$$

The values given in Figures 2 and 4 are based on actual values computed by the TMS32010 for the two sample sine-wave generator programs. The computation of THD was carried out on a VAX 11/780 using the above formulas with double-precision floating-point arithmetic.

APPENDIX B: TMS32010 TABLE LOOKUP ROUTINE

```
GENER1      320 FAMILY MACRO ASSEMBLER  2.1 83.076      17:14:48   1/18/84
                                                                PAGE 0001

                        IDT     'GENER1'
                ***********************************************************
                *          SINE WAVE GENERATOR                            *
                *        DIRECT TABLE LOOKUP METHOD                       *
                * THIS PROGRAM USES A LOOKUP TABLE OF SINE VALUES TO       *
                * COMPUTE THE SAMPLES OF THE WAVE.  THE FREQUENCY IS       *
                * DETERMINED BY THE SIZE BY WHICH ONE STEPS THROUGH THE    *
                * TABLE. THE TABLE CONSISTS OF 128 ENTRIES THAT CORRESPOND *
                * TO EQUALLY SPACED ANGLES BETWEEN 0 AND 360 DEGREES.      *
                ***********************************************************
                *          NOTE:  Q NOTATION                              *
                * THE TMS32010 USES FIXED-POINT TWO'S COMPLEMENT NUMBERS.  *
                * EACH 16-BIT NUMBER HAS A SIGN BIT, i INTEGER BITS, AND   *
                * (15-i) FRACTIONAL BITS.  THE VALUE AFTER THE LETTER Q    *
                * REFERS TO THE NUMBER OF FRACTIONAL BITS THAT ARE         *
                * REPRESENTED BY THAT NUMBER, i.e., A Q14 NUMBER IS        *
                * CONSIDERED TO HAVE 14 FRACTIONAL BITS.                   *
                ***********************************************************
0000 F900               B       START
0001 0083'
0002 0000       SINE    DATA    >0              *THE SINE TABLE
0003 0324               DATA    >324            *VALUES ARE REPRESENTED IN
0004 0646               DATA    >646            *Q14 FORMAT, i.e., THERE
0005 0964               DATA    >964            *ARE 14 BITS AFTER THE
0006 0C7C               DATA    >C7C            *BINARY POINT.
0007 0F8D               DATA    >F8D
0008 1294               DATA    >1294
0009 1590               DATA    >1590
000A 187E               DATA    >187E
000B 1B5D               DATA    >1B5D
000C 1E2B               DATA    >1E2B
000D 20E7               DATA    >20E7
000E 238E               DATA    >238E
000F 2620               DATA    >2620
0010 289A               DATA    >289A
0011 2AFB               DATA    >2AFB
0012 2D41               DATA    >2D41
0013 2F6C               DATA    >2F6C
0014 3179               DATA    >3179
0015 3368               DATA    >3368
0016 3537               DATA    >3537
0017 36E5               DATA    >36E5
0018 3871               DATA    >3871
0019 39DB               DATA    >39DB
001A 3B21               DATA    >3B21
001B 3C42               DATA    >3C42
001C 3D3F               DATA    >3D3F
001D 3E15               DATA    >3E15
001E 3EC5               DATA    >3EC5
001F 3F4F               DATA    >3F4F
0020 3FB1               DATA    >3FB1
0021 3FEC               DATA    >3FEC
0022 4000               DATA    >4000
0023 3FEC               DATA    >3FEC
```

```
0054 0024 3FB1          DATA    >3FB1
0055 0025 3F4F          DATA    >3F4F
0056 0026 3EC5          DATA    >3EC5
0057 0027 3E15          DATA    >3E15
0058 0028 3D3F          DATA    >3D3F
0059 0029 3C42          DATA    >3C42
0060 002A 3B21          DATA    >3B21
0061 002B 39DB          DATA    >39DB
0062 002C 3871          DATA    >3871
0063 002D 36E5          DATA    >36E5
0064 002E 3537          DATA    >3537
0065 002F 3368          DATA    >3368
0066 0030 3179          DATA    >3179
0067 0031 2F6C          DATA    >2F6C
0068 0032 2D41          DATA    >2D41
0069 0033 2AFB          DATA    >2AFB
0070 0034 289A          DATA    >289A
0071 0035 2620          DATA    >2620
0072 0036 238E          DATA    >238E
0073 0037 20E7          DATA    >20E7
0074 0038 1E2B          DATA    >1E2B
0075 0039 1B5D          DATA    >1B5D
0076 003A 187E          DATA    >187E
0077 003B 1590          DATA    >1590
0078 003C 1294          DATA    >1294
0079 003D 0F8D          DATA    >F8D
0080 003E 0C7C          DATA    >C7C
0081 003F 0964          DATA    >964
0082 0040 0646          DATA    >646
0083 0041 0324          DATA    >324
0084 0042 0000          DATA    >0
0085 0043 FCDC          DATA    >FCDC
0086 0044 F9BA          DATA    >F9BA
0087 0045 F69C          DATA    >F69C
0088 0046 F384          DATA    >F384
0089 0047 F073          DATA    >F073
0090 0048 ED6C          DATA    >ED6C
0091 0049 EA70          DATA    >EA70
0092 004A E782          DATA    >E782
0093 004B E4A3          DATA    >E4A3
0094 004C E1D5          DATA    >E1D5
0095 004D DF19          DATA    >DF19
0096 004E DC72          DATA    >DC72
0097 004F D9E0          DATA    >D9E0
0098 0050 D766          DATA    >D766
0099 0051 D505          DATA    >D505
0100 0052 D2BF          DATA    >D2BF
0101 0053 D094          DATA    >D094
0102 0054 CE87          DATA    >CE87
0103 0055 CC98          DATA    >CC98
0104 0056 CAC9          DATA    >CAC9
0105 0057 C91B          DATA    >C91B
0106 0058 C78F          DATA    >C78F
0107 0059 C625          DATA    >C625
```

```
0108 005A C4DF          DATA    >C4DF
0109 005B C3BE          DATA    >C3BE
0110 005C C2C1          DATA    >C2C1
0111 005D C1EB          DATA    >C1EB
0112 005E C13B          DATA    >C13B
0113 005F C0B1          DATA    >C0B1
0114 0060 C04F          DATA    >C04F
0115 0061 C014          DATA    >C014
0116 0062 C000          DATA    >C000
0117 0063 C014          DATA    >C014
0118 0064 C04F          DATA    >C04F
0119 0065 C0B1          DATA    >C0B1
0120 0066 C13B          DATA    >C13B
0121 0067 C1EB          DATA    >C1EB
0122 0068 C2C1          DATA    >C2C1
0123 0069 C3BE          DATA    >C3BE
0124 006A C4DF          DATA    >C4DF
0125 006B C625          DATA    >C625
0126 006C C78F          DATA    >C78F
0127 006D C91B          DATA    >C91B
0128 006E CAC9          DATA    >CAC9
0129 006F CC98          DATA    >CC98
0130 0070 CE87          DATA    >CE87
0131 0071 D094          DATA    >D094
0132 0072 D2BF          DATA    >D2BF
0133 0073 D505          DATA    >D505
0134 0074 D766          DATA    >D766
0135 0075 D9E0          DATA    >D9E0
0136 0076 DC72          DATA    >DC72
0137 0077 DF19          DATA    >DF19
0138 0078 E1D5          DATA    >E1D5
0139 0079 E4A3          DATA    >E4A3
0140 007A E782          DATA    >E782
0141 007B EA70          DATA    >EA70
0142 007C ED6C          DATA    >ED6C
0143 007D F073          DATA    >F073
0144 007E F384          DATA    >F384
0145 007F F69C          DATA    >F69C
0146 0080 F9BA          DATA    >F9BA
0147 0081 FCDC          DATA    >FCDC
0148 0082
0149 0082 7FFF  M1      DATA    >7FFF
0150 0083
0151              ******************************
0152              *DATA MEMORY LOCATIONS USED*
0153              ******************************
0154      0000    DELTA   EQU     0
0155      0001    ALPHA   EQU     1
0156      0002    SINA    EQU     2
0157      0003    TEMP    EQU     3               *WORKSPACE REGISTER
0158      0004    MASK    EQU     4
0159      0005    OFSET   EQU     5
0160 0083
```

```
0161                ************************************************************
0162                * NECESSARY INITIALIZATIONS:                               *
0163                * MASK    INITIALIZED TO >7FFF FOR 128 POINT TABLE         *
0164                * OFSET   INITIALIZED TO THE ADDRESS AT THE BEGINNING      *
0165                *         OF TABLE.                                        *
0166                * ALPHA   INITIALLY CLEARED                                *
0167                * DELTA   INITIALIZED TO INCREMENT VALUE USING Q8 FORMAT   *
0168                ************************************************************
0169 0083 6F00     START  LDP     0                * SET DATA PAGE POINTER
0170 0084 7E82            LACK    M1
0171 0085 6704            TBLR    MASK
0172 0086 7E02            LACK    SINE
0173 0087 5005            SACL    OFSET
0174 0088 7F89            ZAC
0175 0089 5001            SACL    ALPHA
0176 008A 4100            IN      DELTA,PA1                * IN THIS EXAMPLE,
0177 008B F800     L1     CALL    SWAVE1                   * DELTA IS INPUT
     008C 008F'
0178                ***********************************
0179                *       REST OF PROGRAM           *
0180                ***********************************
0181 008D F900            B       L1
     008E 008B'
0182 008F
0183                ************************************************************
0184                * SINE WAVE SUBROUTINE:                                    *
0185                * THIS ROUTINE EXTRACTS THE SINE OF AN ANGLE FROM THE      *
0186                * TABLE AND RETURNS THE VALUE IN THE DATA LOCATION         *
0187                * 'SINA'.  IT USES A FRACTIONAL STEP SIZE TO COMPUTE       *
0188                * THE NEXT POINT OF THE WAVE.  IT TAKES 2.6 microseconds   *
0189                * TO EXECUTE.                                              *
0190                ************************************************************
0191 008F 2801     SWAVE1 LAC     ALPHA,8
0192 0090 5803            SACH    TEMP             *ISOLATE INTEGER PORTION
0193 0091 2003            LAC     TEMP
0194 0092 0005            ADD     OFSET
0195 0093 6702            TBLR    SINA             *SINE VALUE FROM TABLE (Q14)
0196 0094 2001            LAC     ALPHA
0197 0095 0000            ADD     DELTA            *COMPUTE NEXT ADDRRESS
0198 0096 7904            AND     MASK             *MODULO 128 MASK = >7FFF
0199 0097 5001            SACL    ALPHA            *SAVE NEXT ADDRESS
0200 0098 7F8D            RET                      *RETURN TO MAIN PROGRAM
0201                      END
NO ERRORS, NO WARNINGS
```

APPENDIX C: TMS32010 LINEAR INTERPOLATION ROUTINE

```
GENER2      320 FAMILY MACRO ASSEMBLER  2.1 83.076      10:54:48   1/19/84
                                                                PAGE 0001

                        IDT     'GENER2'
                 ******************************************************
                 *       SINE WAVE GENERATOR                          *
                 *       LINEAR INTERPOLATION METHOD                  *
                 * THIS PROGRAM USES A LOOKUP TABLE OF SINE VALUES TO *
                 * COMPUTE THE SAMPLES OF THE WAVE.  THE FREQUENCY IS *
                 * DETERMINED BY THE SIZE BY WHICH ONE STEPS THROUGH  *
                 * THE TABLE.  THE TABLE CONSISTS OF 128 ENTRIES THAT *
                 * CORRESPOND TO EQUALLY SPACED ANGLES BETWEEN 0 AND  *
                 * 360 DEGREES.  POINTS BETWEEN THE TABLE ENTRIES ARE *
                 * APPROXIMATED USING A LINEAR APPROXIMATION,         *
                 * sin(A) ~= sin(INT[A])                              *
                 *           + {sin(INT[A]+1)-sin(INT[A])}xFRACT[A]   *
                 * ALL THE POSSIBLE SLOPES BETWEEN ANY TWO CONSECUTIVE*
                 * SINE TABLE ENTRIES ARE STORED IN A SEPARATE TABLE. *
                 * THE SLOPE TABLE IS ALSO 128 ENTRIES LONG.          *
                 ******************************************************
                 *       NOTE:  Q NOTATION                            *
                 * THE TMS32010 USES FIXED-POINT TWO'S COMPLEMENT     *
                 * NUMBERS.  EACH 16-BIT NUMBER HAS A SIGN BIT, i     *
                 * INTEGER BITS, AND (15-i) FRACTIONAL BITS.  THE     *
                 * VALUE AFTER THE LETTER Q REFERS TO THE NUMBER OF   *
                 * FRACTIONAL BITS THAT ARE REPRESENTED BY THAT       *
                 * NUMBER, i.e., A Q14 NUMBER IS CONSIDERED TO HAVE   *
                 * 14 FRACTIONAL BITS.                                *
                 ******************************************************
0000
0000 F900                B       START
0001 0104'
                 *
0002 7FFF        M1      DATA    >7FFF           *MASK VALUES
0003 0FFF        M2      DATA    >0FFF
                 *
0004 0000        SINE    DATA    >0              *THE SINE TABLE
0005 0324                DATA    >324            *VALUES ARE REPRESENTED
0006 0646                DATA    >646            *IN Q14 FORMAT, i.e.,
0007 0964                DATA    >964            *THERE ARE 14 BITS AFTER
0008 0C7C                DATA    >C7C            *THE BINARY POINT.
0009 0F8D                DATA    >F8D
000A 1294                DATA    >1294
000B 1590                DATA    >1590
000C 187E                DATA    >187E
000D 1B5D                DATA    >1B5D
000E 1E2B                DATA    >1E2B
000F 20E7                DATA    >20E7
0010 238E                DATA    >238E
0011 2620                DATA    >2620
0012 289A                DATA    >289A
0013 2AFB                DATA    >2AFB
0014 2D41                DATA    >2D41
0015 2F6C                DATA    >2F6C
0016 3179                DATA    >3179
0017 3368                DATA    >3368
0018 3537                DATA    >3537
```

```
0054 0019 36E5          DATA    >36E5
0055 001A 3871          DATA    >3871
0056 001B 39DB          DATA    >39DB
0057 001C 3B21          DATA    >3B21
0058 001D 3C42          DATA    >3C42
0059 001E 3D3F          DATA    >3D3F
0060 001F 3E15          DATA    >3E15
0061 0020 3EC5          DATA    >3EC5
0062 0021 3F4F          DATA    >3F4F
0063 0022 3FB1          DATA    >3FB1
0064 0023 3FEC          DATA    >3FEC
0065 0024 4000          DATA    >4000
0066 0025 3FEC          DATA    >3FEC
0067 0026 3FB1          DATA    >3FB1
0068 0027 3F4F          DATA    >3F4F
0069 0028 3EC5          DATA    >3EC5
0070 0029 3E15          DATA    >3E15
0071 002A 3D3F          DATA    >3D3F
0072 002B 3C42          DATA    >3C42
0073 002C 3B21          DATA    >3B21
0074 002D 39DB          DATA    >39DB
0075 002E 3871          DATA    >3871
0076 002F 36E5          DATA    >36E5
0077 0030 3537          DATA    >3537
0078 0031 3368          DATA    >3368
0079 0032 3179          DATA    >3179
0080 0033 2F6C          DATA    >2F6C
0081 0034 2D41          DATA    >2D41
0082 0035 2AFB          DATA    >2AFB
0083 0036 289A          DATA    >289A
0084 0037 2620          DATA    >2620
0085 0038 238E          DATA    >238E
0086 0039 20E7          DATA    >20E7
0087 003A 1E2B          DATA    >1E2B
0088 003B 1B5D          DATA    >1B5D
0089 003C 187E          DATA    >187E
0090 003D 1590          DATA    >1590
0091 003E 1294          DATA    >1294
0092 003F 0F8D          DATA    >F8D
0093 0040 0C7C          DATA    >C7C
0094 0041 0964          DATA    >964
0095 0042 0646          DATA    >646
0096 0043 0324          DATA    >324
0097 0044 0000          DATA    >0
0098 0045 FCDC          DATA    >FCDC
0099 0046 F9BA          DATA    >F9BA
0100 0047 F69C          DATA    >F69C
0101 0048 F384          DATA    >F384
0102 0049 F073          DATA    >F073
0103 004A ED6C          DATA    >ED6C
0104 004B EA70          DATA    >EA70
0105 004C E782          DATA    >E782
0106 004D E4A3          DATA    >E4A3
0107 004E E1D5          DATA    >E1D5
```

```
0108 004F DF19          DATA    >DF19
0109 0050 DC72          DATA    >DC72
0110 0051 D9E0          DATA    >D9E0
0111 0052 D766          DATA    >D766
0112 0053 D505          DATA    >D505
0113 0054 D2BF          DATA    >D2BF
0114 0055 D094          DATA    >D094
0115 0056 CE87          DATA    >CE87
0116 0057 CC98          DATA    >CC98
0117 0058 CAC9          DATA    >CAC9
0118 0059 C91B          DATA    >C91B
0119 005A C78F          DATA    >C78F
0120 005B C625          DATA    >C625
0121 005C C4DF          DATA    >C4DF
0122 005D C3BE          DATA    >C3BE
0123 005E C2C1          DATA    >C2C1
0124 005F C1EB          DATA    >C1EB
0125 0060 C13B          DATA    >C13B
0126 0061 C0B1          DATA    >C0B1
0127 0062 C04F          DATA    >C04F
0128 0063 C014          DATA    >C014
0129 0064 C000          DATA    >C000
0130 0065 C014          DATA    >C014
0131 0066 C04F          DATA    >C04F
0132 0067 C0B1          DATA    >C0B1
0133 0068 C13B          DATA    >C13B
0134 0069 C1EB          DATA    >C1EB
0135 006A C2C1          DATA    >C2C1
0136 006B C3BE          DATA    >C3BE
0137 006C C4DF          DATA    >C4DF
0138 006D C625          DATA    >C625
0139 006E C78F          DATA    >C78F
0140 006F C91B          DATA    >C91B
0141 0070 CAC9          DATA    >CAC9
0142 0071 CC98          DATA    >CC98
0143 0072 CE87          DATA    >CE87
0144 0073 D094          DATA    >D094
0145 0074 D2BF          DATA    >D2BF
0146 0075 D505          DATA    >D505
0147 0076 D766          DATA    >D766
0148 0077 D9E0          DATA    >D9E0
0149 0078 DC72          DATA    >DC72
0150 0079 DF19          DATA    >DF19
0151 007A E1D5          DATA    >E1D5
0152 007B E4A3          DATA    >E4A3
0153 007C E782          DATA    >E782
0154 007D EA70          DATA    >EA70
0155 007E ED6C          DATA    >ED6C
0156 007F F073          DATA    >F073
0157 0080 F384          DATA    >F384
0158 0081 F69C          DATA    >F69C
0159 0082 F9BA          DATA    >F9BA
0160 0083 FCDC          DATA    >FCDC
0161 0084 0324  TSLOPE  DATA    >324            *SLOPE BETWEEN TWO
```

```
0162 0085 0322          DATA    >322            *SINE ENTRIES (Q14)
0163 0086 031E          DATA    >31E
0164 0087 0318          DATA    >318
0165 0088 0311          DATA    >311
0166 0089 0307          DATA    >307
0167 008A 02FC          DATA    >2FC
0168 008B 02EE          DATA    >2EE
0169 008C 02DF          DATA    >2DF
0170 008D 02CE          DATA    >2CE
0171 008E 02BC          DATA    >2BC
0172 008F 02A7          DATA    >2A7
0173 0090 0291          DATA    >291
0174 0091 027A          DATA    >27A
0175 0092 0261          DATA    >261
0176 0093 0246          DATA    >246
0177 0094 022B          DATA    >22B
0178 0095 020D          DATA    >20D
0179 0096 01EF          DATA    >1EF
0180 0097 01CF          DATA    >1CF
0181 0098 01AE          DATA    >1AE
0182 0099 018C          DATA    >18C
0183 009A 016A          DATA    >16A
0184 009B 0146          DATA    >146
0185 009C 0121          DATA    >121
0186 009D 00FC          DATA    >FC
0187 009E 00D6          DATA    >D6
0188 009F 00B0          DATA    >B0
0189 00A0 0089          DATA    >89
0190 00A1 0062          DATA    >62
0191 00A2 003B          DATA    >3B
0192 00A3 0014          DATA    >14
0193 00A4 FFEC          DATA    >FFEC
0194 00A5 FFC5          DATA    >FFC5
0195 00A6 FF9E          DATA    >FF9E
0196 00A7 FF77          DATA    >FF77
0197 00A8 FF50          DATA    >FF50
0198 00A9 FF2A          DATA    >FF2A
0199 00AA FF04          DATA    >FF04
0200 00AB FEDF          DATA    >FEDF
0201 00AC FEBA          DATA    >FEBA
0202 00AD FE96          DATA    >FE96
0203 00AE FE74          DATA    >FE74
0204 00AF FE52          DATA    >FE52
0205 00B0 FE31          DATA    >FE31
0206 00B1 FE11          DATA    >FE11
0207 00B2 FDF3          DATA    >FDF3
0208 00B3 FDD5          DATA    >FDD5
0209 00B4 FDBA          DATA    >FDBA
0210 00B5 FD9F          DATA    >FD9F
0211 00B6 FD86          DATA    >FD86
0212 00B7 FD6F          DATA    >FD6F
0213 00B8 FD59          DATA    >FD59
0214 00B9 FD44          DATA    >FD44
0215 00BA FD32          DATA    >FD32
```

```
0216 00BB FD21          DATA    >FD21
0217 00BC FD12          DATA    >FD12
0218 00BD FD04          DATA    >FD04
0219 00BE FCF9          DATA    >FCF9
0220 00BF FCEF          DATA    >FCEF
0221 00C0 FCE8          DATA    >FCE8
0222 00C1 FCE2          DATA    >FCE2
0223 00C2 FCDE          DATA    >FCDE
0224 00C3 FCDC          DATA    >FCDC
0225 00C4 FCDC          DATA    >FCDC
0226 00C5 FCDE          DATA    >FCDE
0227 00C6 FCE2          DATA    >FCE2
0228 00C7 FCE8          DATA    >FCE8
0229 00C8 FCEF          DATA    >FCEF
0230 00C9 FCF9          DATA    >FCF9
0231 00CA FD04          DATA    >FD04
0232 00CB FD12          DATA    >FD12
0233 00CC FD21          DATA    >FD21
0234 00CD FD32          DATA    >FD32
0235 00CE FD44          DATA    >FD44
0236 00CF FD59          DATA    >FD59
0237 00D0 FD6F          DATA    >FD6F
0238 00D1 FD86          DATA    >FD86
0239 00D2 FD9F          DATA    >FD9F
0240 00D3 FDBA          DATA    >FDBA
0241 00D4 FDD5          DATA    >FDD5
0242 00D5 FDF3          DATA    >FDF3
0243 00D6 FE11          DATA    >FE11
0244 00D7 FE31          DATA    >FE31
0245 00D8 FE52          DATA    >FE52
0246 00D9 FE74          DATA    >FE74
0247 00DA FE96          DATA    >FE96
0248 00DB FEBA          DATA    >FEBA
0249 00DC FEDF          DATA    >FEDF
0250 00DD FF04          DATA    >FF04
0251 00DE FF2A          DATA    >FF2A
0252 00DF FF50          DATA    >FF50
0253 00E0 FF77          DATA    >FF77
0254 00E1 FF9E          DATA    >FF9E
0255 00E2 FFC5          DATA    >FFC5
0256 00E3 FFEC          DATA    >FFEC
0257 00E4 0014          DATA    >14
0258 00E5 003B          DATA    >3B
0259 00E6 0062          DATA    >62
0260 00E7 0089          DATA    >89
0261 00E8 00B0          DATA    >B0
0262 00E9 00D6          DATA    >D6
0263 00EA 00FC          DATA    >FC
0264 00EB 0121          DATA    >121
0265 00EC 0146          DATA    >146
0266 00ED 016A          DATA    >16A
0267 00EE 018C          DATA    >18C
0268 00EF 01AE          DATA    >1AE
0269 00F0 01CF          DATA    >1CF
```

```
0270 00F1 01EF          DATA    >1EF
0271 00F2 020D          DATA    >20D
0272 00F3 022B          DATA    >22B
0273 00F4 0246          DATA    >246
0274 00F5 0261          DATA    >261
0275 00F6 027A          DATA    >27A
0276 00F7 0291          DATA    >291
0277 00F8 02A7          DATA    >2A7
0278 00F9 02BC          DATA    >2BC
0279 00FA 02CE          DATA    >2CE
0280 00FB 02DF          DATA    >2DF
0281 00FC 02EE          DATA    >2EE
0282 00FD 02FC          DATA    >2FC
0283 00FE 0307          DATA    >307
0284 00FF 0311          DATA    >311
0285 0100 0318          DATA    >318
0286 0101 031E          DATA    >31E
0287 0102 0322          DATA    >322
0288 0103 0324          DATA    >324
0289 0104
0290                ******************************
0291                *DATA MEMORY LOCATIONS USED *
0292                ******************************
0293       0000 DELTA   EQU     0
0294       0001 ALPHA   EQU     1
0295       0002 SLOPE   EQU     2
0296       0003 SINA    EQU     3
0297       0004 TEMP    EQU     4               *SCRATCH PAD LOCATION
0298       0005 MASK1   EQU     5               *MASK FOR MODULO 128 POINTER
0299       0006 MASK2   EQU     6               *ISOLATE FRACTIONAL PART
0300       0007 OFSET1  EQU     7               *ADDRESS OF SINE TABLE
0301       0008 OFSET2  EQU     8               *ADDRESS OF SLOPE TABLE
0302                ********************************************************
0303                * NECESSARY INITIALIZATIONS:                           *
0304                * MASK1    INITIALIZED TO >7FFF FOR 128 POINT TABLE    *
0305                * MASK2    INITIALIZED TO >0FFF                        *
0306                * OFSET1   SET TO THE ADDRESS AT THE BEGINNING OF      *
0307                *          SINE TABLE                                  *
0308                * OFSET2   SET TO THE ADDRESS AT THE BEGINNING OF      *
0309                *          SLOPE TABLE WITH RESPECT TO SINE TABLE      *
0310                * ALPHA    INITIALLY CLEARED                           *
0311                * DELTA    INITIALIZED TO INCREMENT VALUE USING        *
0312                *          Q8 FORMAT                                   *
0313                ********************************************************
0314 0104
0315 0104 6F00 START LDP     0               *SET DATA PAGE POINTER.
0316 0105 7E04       LACK    SINE            *SINE TABLE ADDRESS.
0317 0106 5007       SACL    OFSET1
0318 0107 7E84       LACK    TSLOPE          *SLOPE TABLE ADDRESS.
0319 0108 1007       SUB     OFSET1
0320 0109 5008       SACL    OFSET2
0321 010A 7E02       LACK    M1              *RETRIEVE MASK1.
0322 010B 6705       TBLR    MASK1
0323 010C 7E03       LACK    M2              *RETRIEVE MASK2.
```

```
0324 010D 6706          TBLR    MASK2
0325 010E 7F89          ZAC
0326 010F 5001          SACL    ALPHA           *START ANGLE AT ZERO.
0327 0110 4100          IN      DELTA,PA1       *FOR THIS EXAMPLE,
0328 0111 F800  L1      CALL    SWAVE2          *DELTA IS INPUT.
     0112 0115'
0329                ****************************
0330                *      REST OF PROGRAM     *
0331                ****************************
0332 0113 F900          B       L1
     0114 0111'
0333 0115
0334 0115
0335                ******************************************************
0336                * SINE WAVE SUBROUTINE:                              *
0337                * THIS ROUTINE COMPUTES THE SINE OF AN ANGLE AND     *
0338                * RETURNS THE VALUE IN DATA LOCATION 'SINA'.  IT USES *
0339                * A FRACTIONAL STEP SIZE TO AUTOMATICALLY COMPUTE THE *
0340                * ADDRESS OF THE NEXT POINT OF THE SINE WAVE. IT     *
0341                * TAKES 5.0 microseconds TO EXECUTE.                 *
0342                ******************************************************
0343 0115 2801 SWAVE2 LAC      ALPHA,8
0344 0116 5804          SACH    TEMP            *ISOLATE INTEGER PORTION
0345 0117 2004          LAC     TEMP
0346 0118 0007          ADD     OFSET1
0347 0119 6703          TBLR    SINA            *GET CLOSEST LOWER SINE-
0348 011A 0008          ADD     OFSET2          *TABLE ENTRY (b).
0349 011B 6702          TBLR    SLOPE           *SLOPE FOR CORRESPONDING INTERVA
0350 011C 2401          LAC     ALPHA,4         *ISOLATE FRACTIONAL PORTION
0351 011D 7906          AND     MASK2           *AND MAKE Q8 NUMBER INTO Q12.
0352 011E 5004          SACL    TEMP
0353 011F 6A04          LT      TEMP
0354 0120 6D02          MPY     SLOPE           * mx
0355 0121 7F8E          PAC
0356 0122 0C03          ADD     SINA,12
0357 0123 5C03          SACH    SINA,4          * y = mx + b.
0358 0124 2001          LAC     ALPHA           *COMPUTE ADDRESS OF NEXT POINT.
0359 0125 0000          ADD     DELTA           *OF WAVE.
0360 0126 7905          AND     MASK1           *CLEAR MOST SIGNIFICANT BIT.
0361 0127 5001          SACL    ALPHA           *SAVE NEXT ADDRESS.
0362 0128 7F8D          RET                     *RETURN TO MAIN PROGRAM.
0363                    END
NO ERRORS, NO WARNINGS
```