Precision Digital Sine-Wave Generation with the TMS32010

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TEXAS INSTRUMENTS

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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[mod(k X DELTA,N)]   for k = 1, 2, 3, 4, ...

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.

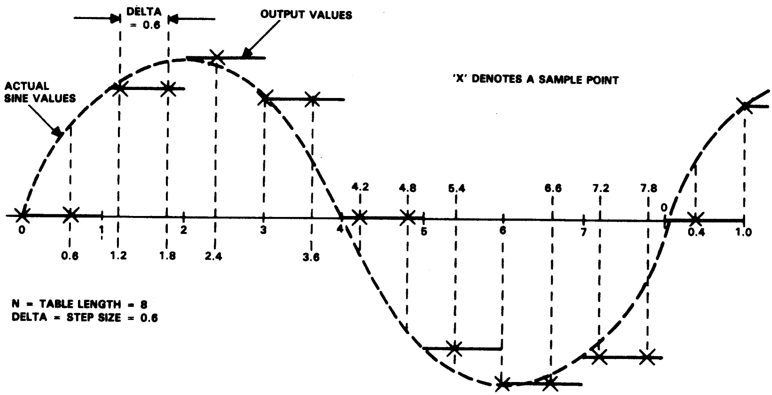

Figure 1. Direct Table Lookup

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:

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

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

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

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

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

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

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

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

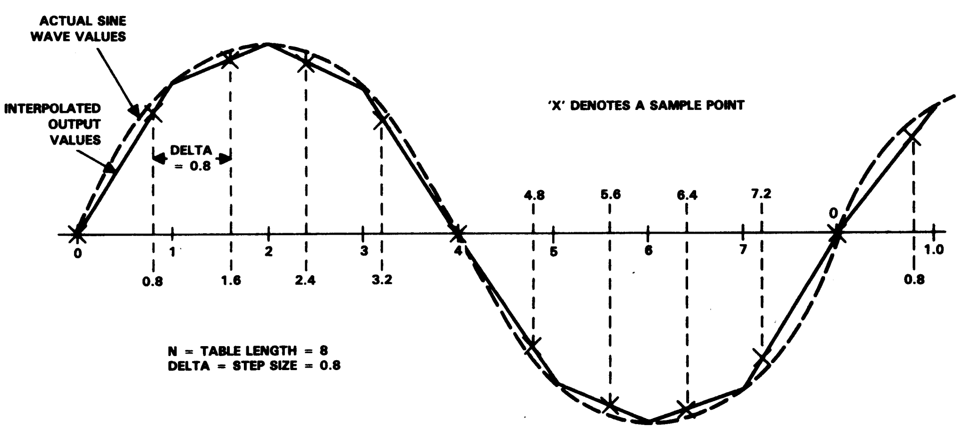

Figure 3. Linear Interpolation

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:

$$THD = [E(total) - E(fundamental)] / E(total)$$

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

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

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

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

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


```
                      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
```

```
0024 3FB1          DATA     >3FB1
0025 3F4F          DATA     >3F4F
0026 3EC5          DATA     >3EC5
0027 3E15          DATA     >3E15
0028 3D3F          DATA     >3D3F
0029 3C42          DATA     >3C42
002A 3B21          DATA     >3B21
002B 39DB          DATA     >39DB
002C 3871          DATA     >3871
002D 36E5          DATA     >36E5
002E 3537          DATA     >3537
002F 3368          DATA     >3368
0030 3179          DATA     >3179
0031 2F6C          DATA     >2F6C
0032 2D41          DATA     >2D41
0033 2AFB          DATA     >2AFB
0034 289A          DATA     >289A
0035 2620          DATA     >2620
0036 238E          DATA     >238E
0037 20E7          DATA     >20E7
0038 1E2B          DATA     >1E2B
0039 1B5D          DATA     >1B5D
003A 187E          DATA     >187E
003B 1590          DATA     >1590
003C 1294          DATA     >1294
003D 0F8D          DATA     >F8D
003E 0C7C          DATA     >C7C
003F 0964          DATA     >964
0040 0646          DATA     >646
0041 0324          DATA     >324
0042 0000          DATA     >0
0043 FCDC          DATA     >FCDC
0044 F9BA          DATA     >F9BA
0045 F69C          DATA     >F69C
0046 F384          DATA     >F384
0047 F073          DATA     >F073
0048 ED6C          DATA     >ED6C
0049 EA70          DATA     >EA70
004A E782          DATA     >E782
004B E4A3          DATA     >E4A3
004C E1D5          DATA     >E1D5
004D DF19          DATA     >DF19
004E DC72          DATA     >DC72
004F D9E0          DATA     >D9E0
0050 D766          DATA     >D766
0051 D505          DATA     >D505
0052 D2BF          DATA     >D2BF
0053 D094          DATA     >D094
0054 CE87          DATA     >CE87
0055 CC98          DATA     >CC98
0056 CAC9          DATA     >CAC9
0057 C91B          DATA     >C91B
0058 C78F          DATA     >C78F
0059 C625          DATA     >C625
```

```
005A C4DF           DATA     >C4DF
005B C3BE           DATA     >C3BE
005C C2C1           DATA     >C2C1
005D C1EB           DATA     >C1EB
005E C13B           DATA     >C13B
005F C0B1           DATA     >C0B1
0060 C04F           DATA     >C04F
0061 C014           DATA     >C014
0062 C000           DATA     >C000
0063 C014           DATA     >C014
0064 C04F           DATA     >C04F
0065 C0B1           DATA     >C0B1
0066 C13B           DATA     >C13B
0067 C1EB           DATA     >C1EB
0068 C2C1           DATA     >C2C1
0069 C3BE           DATA     >C3BE
006A C4DF           DATA     >C4DF
006B C625           DATA     >C625
006C C78F           DATA     >C78F
006D C91B           DATA     >C91B
006E CAC9           DATA     >CAC9
006F CC98           DATA     >CC98
0070 CE87           DATA     >CE87
0071 D094           DATA     >D094
0072 D2BF           DATA     >D2BF
0073 D505           DATA     >D505
0074 D766           DATA     >D766
0075 D9E0           DATA     >D9E0
0076 DC72           DATA     >DC72
0077 DF19           DATA     >DF19
0078 E1D5           DATA     >E1D5
0079 E4A3           DATA     >E4A3
007A E782           DATA     >E782
007B EA70           DATA     >EA70
007C ED6C           DATA     >ED6C
007D F073           DATA     >F073
007E F384           DATA     >F384
007F F69C           DATA     >F69C
0080 F9BA           DATA     >F9BA
0081 FCDC           DATA     >FCDC
0082
0082 7FFF  M1       DATA     >7FFF
0083
                *****************************
                *DATA MEMORY LOCATIONS USED*
                *****************************
     0000  DELTA    EQU      0
     0001  ALPHA    EQU      1
     0002  SINA     EQU      2
     0003  TEMP     EQU      3                    *WORKSPACE REGISTER
     0004  MASK     EQU      4
     0005  OFSET    EQU      5
0083
```

```
                  ************************************************************
                  * NECESSARY INITIALIZATIONS:                               *
                  * MASK    INITIALIZED TO >7FFF FOR 128 POINT TABLE         *
                  * OFSET   INITIALIZED TO THE ADDRESS AT THE BEGINNING      *
                  *         OF TABLE.                                        *
                  * ALPHA   INITIALLY CLEARED                                *
                  * DELTA   INITIALIZED TO INCREMENT VALUE USING Q8 FORMAT   *
                  ************************************************************
0083 6F00         START  LDP    0                 * SET DATA PAGE POINTER
0084 7E82                LACK   M1
0085 6704                TBLR   MASK
0086 7E02                LACK   SINE
0087 5005                SACL   OFSET
0088 7F89                ZAC
0089 5001                SACL   ALPHA
008A 4100                IN     DELTA,PA1                    * IN THIS EXAMPLE,
008B F800         L1     CALL   SWAVE1                       * DELTA IS INPUT
008C 008F'
                  *********************************
                  *        REST OF PROGRAM        *
                  *********************************
008D F900                B      L1
008E 008B'
008F
                  ************************************************************
                  * SINE WAVE SUBROUTINE:                                    *
                  * THIS ROUTINE EXTRACTS THE SINE OF AN ANGLE FROM THE      *
                  * TABLE AND RETURNS THE VALUE IN THE DATA LOCATION        *
                  * 'SINA'.  IT USES A FRACTIONAL STEP SIZE TO COMPUTE      *
                  * THE NEXT POINT OF THE WAVE.  IT TAKES 2.6 microseconds *
                  * TO EXECUTE.                                              *
                  ************************************************************
008F 2801         SWAVE1 LAC    ALPHA,8
0090 5803                SACH   TEMP              *ISOLATE INTEGER PORTION
0091 2003                LAC    TEMP
0092 0005                ADD    OFSET
0093 6702                TBLR   SINA              *SINE VALUE FROM TABLE (Q14)
0094 2001                LAC    ALPHA
0095 0000                ADD    DELTA             *COMPUTE NEXT ADDRRESS
0096 7904                AND    MASK              *MODULO 128 MASK = >7FFF
0097 5001                SACL   ALPHA             *SAVE NEXT ADDRESS
0098 7F8D                RET                      *RETURN TO MAIN PROGRAM
                         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
```

```
004F DF19          DATA   >DF19
0050 DC72          DATA   >DC72
0051 D9E0          DATA   >D9E0
0052 D766          DATA   >D766
0053 D505          DATA   >D505
0054 D2BF          DATA   >D2BF
0055 D094          DATA   >D094
0056 CE87          DATA   >CE87
0057 CC98          DATA   >CC98
0058 CAC9          DATA   >CAC9
0059 C91B          DATA   >C91B
005A C78F          DATA   >C78F
005B C625          DATA   >C625
005C C4DF          DATA   >C4DF
005D C3BE          DATA   >C3BE
005E C2C1          DATA   >C2C1
005F C1EB          DATA   >C1EB
0060 C13B          DATA   >C13B
0061 C0B1          DATA   >C0B1
0062 C04F          DATA   >C04F
0063 C014          DATA   >C014
0064 C000          DATA   >C000
0065 C014          DATA   >C014
0066 C04F          DATA   >C04F
0067 C0B1          DATA   >C0B1
0068 C13B          DATA   >C13B
0069 C1EB          DATA   >C1EB
006A C2C1          DATA   >C2C1
006B C3BE          DATA   >C3BE
006C C4DF          DATA   >C4DF
006D C625          DATA   >C625
006E C78F          DATA   >C78F
006F C91B          DATA   >C91B
0070 CAC9          DATA   >CAC9
0071 CC98          DATA   >CC98
0072 CE87          DATA   >CE87
0073 D094          DATA   >D094
0074 D2BF          DATA   >D2BF
0075 D505          DATA   >D505
0076 D766          DATA   >D766
0077 D9E0          DATA   >D9E0
0078 DC72          DATA   >DC72
0079 DF19          DATA   >DF19
007A E1D5          DATA   >E1D5
007B E4A3          DATA   >E4A3
007C E782          DATA   >E782
007D EA70          DATA   >EA70
007E ED6C          DATA   >ED6C
007F F073          DATA   >F073
0080 F384          DATA   >F384
0081 F69C          DATA   >F69C
0082 F9BA          DATA   >F9BA
0083 FCDC          DATA   >FCDC
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
```

```
00F1 01EF          DATA    >1EF
00F2 020D          DATA    >20D
00F3 022B          DATA    >22B
00F4 0246          DATA    >246
00F5 0261          DATA    >261
00F6 027A          DATA    >27A
00F7 0291          DATA    >291
00F8 02A7          DATA    >2A7
00F9 02BC          DATA    >2BC
00FA 02CE          DATA    >2CE
00FB 02DF          DATA    >2DF
00FC 02EE          DATA    >2EE
00FD 02FC          DATA    >2FC
00FE 0307          DATA    >307
00FF 0311          DATA    >311
0100 0318          DATA    >318
0101 031E          DATA    >31E
0102 0322          DATA    >322
0103 0324          DATA    >324
0104
               ******************************
               *DATA MEMORY LOCATIONS USED *
               ******************************
     0000      DELTA   EQU     0
     0001      ALPHA   EQU     1
     0002      SLOPE   EQU     2
     0003      SINA    EQU     3
     0004      TEMP    EQU     4                *SCRATCH PAD LOCATION
     0005      MASK1   EQU     5                *MASK FOR MODULO 128 POINTER
     0006      MASK2   EQU     6                *ISOLATE FRACTIONAL PART
     0007      OFSET1  EQU     7                *ADDRESS OF SINE TABLE
     0008      OFSET2  EQU     8                *ADDRESS OF SLOPE TABLE
               ******************************************************
               * NECESSARY INITIALIZATIONS:                         *
               * MASK1   INITIALIZED TO >7FFF FOR 128 POINT TABLE   *
               * MASK2   INITIALIZED TO >0FFF                       *
               * OFSET1  SET TO THE ADDRESS AT THE BEGINNING OF     *
               *         SINE TABLE                                 *
               * OFSET2  SET TO THE ADDRESS AT THE BEGINNING OF     *
               *         SLOPE TABLE WITH RESPECT TO SINE TABLE     *
               * ALPHA   INITIALLY CLEARED                          *
               * DELTA   INITIALIZED TO INCREMENT VALUE USING       *
               *         Q8 FORMAT                                  *
               ******************************************************
0104
0104 6F00      START   LDP     0                *SET DATA PAGE POINTER.
0105 7E04              LACK    SINE             *SINE TABLE ADDRESS.
0106 5007              SACL    OFSET1
0107 7E84              LACK    TSLOPE           *SLOPE TABLE ADDRESS.
0108 1007              SUB     OFSET1
0109 5008              SACL    OFSET2
010A 7E02              LACK    M1               *RETRIEVE MASK1.
010B 6705              TBLR    MASK1
010C 7E03              LACK    M2               *RETRIEVE MASK2.
```

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