

Precision Digital Sine-Wave Generation with the TMS32010

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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	$0 \times 360^\circ/N$	$S[0] = \sin(0^\circ/N)$
1	$1 \times 360^\circ/N$	$S[1] = \sin(360^\circ/N)$
2	$2 \times 360^\circ/N$	$S[2] = \sin(720^\circ/N)$
...	...	...
N-2	$(N-2) \times 360^\circ/N$	$S[N-2] = \sin((N-2) \times 360^\circ/N)$
N-1	$(N-1) \times 360^\circ/N$	$S[N-1] = \sin((N-1) \times 360^\circ/N)$

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:

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

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

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

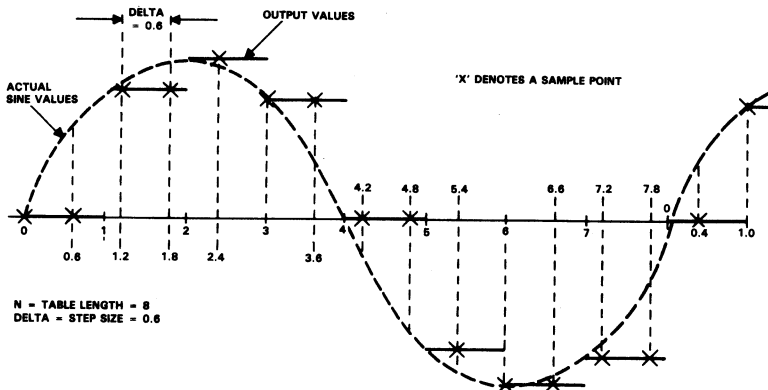


Figure 1. Direct Table Lookup

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:

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

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

In Figure 1, $N = 8$ and $\text{DELTA} = 0.6$. 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 location '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

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

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 $n = 2, 3, 4, \dots$, 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

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

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

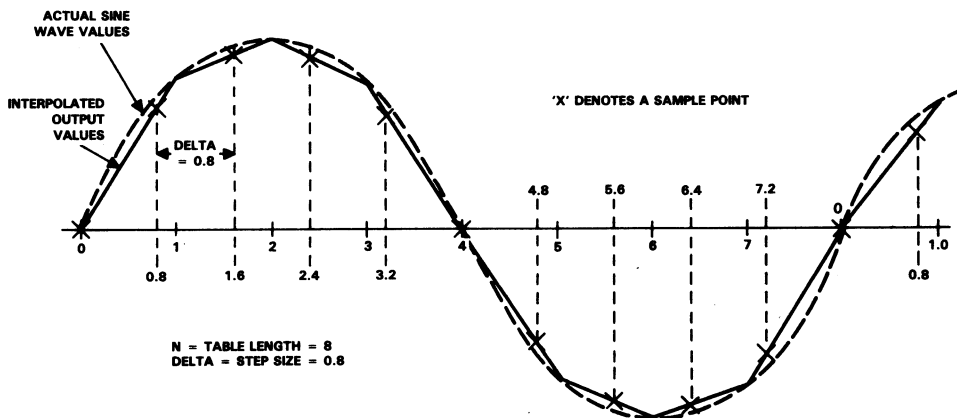


Figure 3. Linear Interpolation

This algorithm is based on the linear approximation

$$\begin{aligned}\sin(360^\circ(I+D)/N) &\cong \sin(360^\circ I/N) \\ &+ D \times \{\sin(360^\circ(I+1)/N) \\ &- \sin(360^\circ I/N)\}\end{aligned}$$

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

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	SIN-2] = sin(360°(N-2)/N)	SIN-1] - SIN-2]
N-1	(N-1) X 360°/N	SIN-1] = sin(360°(N-1)/N)	S[0] - SIN-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 LENGTH: 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:

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

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 $N = \text{table length} = 128$ and if $\text{DELTA} = \text{step size} = 1.5$, a cycle will only be completed for the smallest n for which $n \times 1.5$ is evenly divisible by 128. This occurs for $n = 256$ which marks the end of the second sinusoid period.

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

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

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

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

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

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

```

0001          IDT      'GENER1'
0002          *****
0003          *          SINE WAVE GENERATOR          *
0004          *          DIRECT TABLE LOOKUP METHOD          *
0005          * THIS PROGRAM USES A LOOKUP TABLE OF SINE VALUES TO          *
0006          * COMPUTE THE SAMPLES OF THE WAVE. THE FREQUENCY IS          *
0007          * DETERMINED BY THE SIZE BY WHICH ONE STEPS THROUGH THE          *
0008          * TABLE. THE TABLE CONSISTS OF 128 ENTRIES THAT CORRESPOND          *
0009          * TO EQUALLY SPACED ANGLES BETWEEN 0 AND 360 DEGREES.          *
0010          *****
0011          *          NOTE: Q NOTATION          *
0012          * THE TMS32010 USES FIXED-POINT TWO'S COMPLEMENT NUMBERS.          *
0013          * EACH 16-BIT NUMBER HAS A SIGN BIT, i INTEGER BITS, AND          *
0014          * (15-i) FRACTIONAL BITS. THE VALUE AFTER THE LETTER Q          *
0015          * REFERS TO THE NUMBER OF FRACTIONAL BITS THAT ARE          *
0016          * REPRESENTED BY THAT NUMBER, i.e., A Q14 NUMBER IS          *
0017          * CONSIDERED TO HAVE 14 FRACTIONAL BITS.          *
0018          *****
0019 0000 F900          B          START
0001 0083'
0020 0002 0000      SINE  DATA      >0          *THE SINE TABLE
0021 0003 0324          DATA      >324          *VALUES ARE REPRESENTED IN
0022 0004 0646          DATA      >646          *Q14 FORMAT, i.e., THERE
0023 0005 0964          DATA      >964          *ARE 14 BITS AFTER THE
0024 0006 0C7C          DATA      >C7C          *BINARY POINT.
0025 0007 0F8D          DATA      >F8D
0026 0008 1294          DATA      >1294
0027 0009 1590          DATA      >1590
0028 000A 187E          DATA      >187E
0029 000B 1B5D          DATA      >1B5D
0030 000C 1E2B          DATA      >1E2B
0031 000D 20E7          DATA      >20E7
0032 000E 238E          DATA      >238E
0033 000F 2620          DATA      >2620
0034 0010 289A          DATA      >289A
0035 0011 2AFB          DATA      >2AFB
0036 0012 2D41          DATA      >2D41
0037 0013 2F6C          DATA      >2F6C
0038 0014 3179          DATA      >3179
0039 0015 3368          DATA      >3368
0040 0016 3537          DATA      >3537
0041 0017 36E5          DATA      >36E5
0042 0018 3871          DATA      >3871
0043 0019 39DB          DATA      >39DB
0044 001A 3B21          DATA      >3B21
0045 001B 3C42          DATA      >3C42
0046 001C 3D3F          DATA      >3D3F
0047 001D 3E15          DATA      >3E15
0048 001E 3EC5          DATA      >3EC5
0049 001F 3F4F          DATA      >3F4F
0050 0020 3FB1          DATA      >3FB1
0051 0021 3FEC          DATA      >3FEC
0052 0022 4000          DATA      >4000
0053 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			

 DATA MEMORY LOCATIONS USED

0151				
0152				
0153				
0154	0000	DELTA	EQU	0
0155	0001	ALPHA	EQU	1
0156	0002	SINA	EQU	2
0157	0003	TEMP	EQU	3
0158	0004	MASK	EQU	4
0159	0005	OFFSET	EQU	5

*WORKSPACE REGISTER

0160 0083

```

0161 *****
0162 * NECESSARY INITIALIZATIONS: *
0163 * MASK      INITIALIZED TO >7FFF FOR 128 POINT TABLE *
0164 * OFFSET    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     OFFSET
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
0178 008C 008F'
0178 *****
0179 *           REST OF PROGRAM *
0180 *****
0181 008D F900          B        L1
0182 008E 008B'
0182 008F
0182 *****
0183 * SINE WAVE SUBROUTINE: *
0184 * THIS ROUTINE EXTRACTS THE SINE OF AN ANGLE FROM THE *
0185 * TABLE AND RETURNS THE VALUE IN THE DATA LOCATION *
0186 * 'SINA'. IT USES A FRACTIONAL STEP SIZE TO COMPUTE *
0187 * THE NEXT POINT OF THE WAVE. IT TAKES 2.6 microseconds *
0188 * TO EXECUTE. *
0189 *****
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     OFFSET
0195 0093 6702          TBLR     SINA          *SINE VALUE FROM TABLE (Q14)
0196 0094 2001          LAC      ALPHA
0197 0095 0000          ADD     DELTA        *COMPUTE NEXT ADDRESS
0198 0096 7904          AND     MASK        *MODULO 128 MASK = >7FFF
0199 0097 5001          SACL     ALPHA        *SAVE NEXT ADDRESS
0200 0098 7F8D          RET
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

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0001          IDT      'GENER2'
0002          *****
0003          *      SINE WAVE GENERATOR      *
0004          *      LINEAR INTERPOLATION METHOD      *
0005          *      THIS PROGRAM USES A LOOKUP TABLE OF SINE VALUES TO      *
0006          *      COMPUTE THE SAMPLES OF THE WAVE. THE FREQUENCY IS      *
0007          *      DETERMINED BY THE SIZE BY WHICH ONE STEPS THROUGH      *
0008          *      THE TABLE. THE TABLE CONSISTS OF 128 ENTRIES THAT      *
0009          *      CORRESPOND TO EQUALLY SPACED ANGLES BETWEEN 0 AND      *
0010          *      360 DEGREES. POINTS BETWEEN THE TABLE ENTRIES ARE      *
0011          *      APPROXIMATED USING A LINEAR APPROXIMATION,      *
0012          *      sin(A) ~= sin(INT[A])      *
0013          *      + {sin(INT[A]+1)-sin(INT[A])}*FRACT[A]      *
0014          *      ALL THE POSSIBLE SLOPES BETWEEN ANY TWO CONSECUTIVE*
0015          *      SINE TABLE ENTRIES ARE STORED IN A SEPARATE TABLE. *
0016          *      THE SLOPE TABLE IS ALSO 128 ENTRIES LONG.      *
0017          *****
0018          *      NOTE: Q NOTATION      *
0019          *      THE TMS32010 USES FIXED-POINT TWO'S COMPLEMENT      *
0020          *      NUMBERS. EACH 16-BIT NUMBER HAS A SIGN BIT, i      *
0021          *      INTEGER BITS, AND (15-i) FRACTIONAL BITS. THE      *
0022          *      VALUE AFTER THE LETTER Q REFERS TO THE NUMBER OF      *
0023          *      FRACTIONAL BITS THAT ARE REPRESENTED BY THAT      *
0024          *      NUMBER, i.e., A Q14 NUMBER IS CONSIDERED TO HAVE      *
0025          *      14 FRACTIONAL BITS.      *
0026          *****
0027 0000
0028 0000 F900          B      START
0029 0001 0104'          *
0030 0002 7FFF M1      DATA      >7FFF      *MASK VALUES
0031 0003 0FFF M2      DATA      >0FFF
0032          *
0033 0004 0000 SINE     DATA      >0          *THE SINE TABLE
0034 0005 0324      DATA      >324          *VALUES ARE REPRESENTED
0035 0006 0646      DATA      >646          *IN Q14 FORMAT, i.e.,
0036 0007 0964      DATA      >964          *THERE ARE 14 BITS AFTER
0037 0008 0C7C      DATA      >C7C          *THE BINARY POINT.
0038 0009 0F8D      DATA      >F8D
0039 000A 1294      DATA      >1294
0040 000B 1590      DATA      >1590
0041 000C 187E      DATA      >187E
0042 000D 1B5D      DATA      >1B5D
0043 000E 1E2B      DATA      >1E2B
0044 000F 20E7      DATA      >20E7
0045 0010 238E      DATA      >238E
0046 0011 2620      DATA      >2620
0047 0012 289A      DATA      >289A
0048 0013 2AFB      DATA      >2AFB
0049 0014 2D41      DATA      >2D41
0050 0015 2F6C      DATA      >2F6C
0051 0016 3179      DATA      >3179
0052 0017 3368      DATA      >3368
0053 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 OFFSET1 EQU 7

*ADDRESS OF SINE TABLE

0301 0008 OFFSET2 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 * OFFSET1 SET TO THE ADDRESS AT THE BEGINNING OF *

0307 * SINE TABLE *

0308 * OFFSET2 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 OFFSET1

0318 0107 7E84 LACK TSLOPE

*SLOPE TABLE ADDRESS.

0319 0108 1007 SUB OFFSET1

0320 0109 5008 SACL OFFSET2

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      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      OFFSET1
0347 0119 6703      TBLR    SINA          *GET CLOSEST LOWER SINE-
0348 011A 0008      ADD      OFFSET2     *TABLE ENTRY (b).
0349 011B 6702      TBLR    SLOPE        *SLOPE FOR CORRESPONDING INTERVAL
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