

D/A Conversion Using PWM and R-2R Ladders to Generate Sine and DTMF Waveforms

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INTRODUCTION

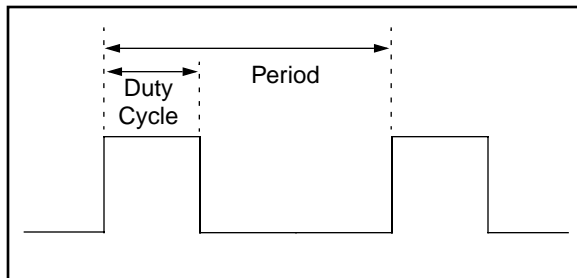
Many embedded applications require the generation of analog signals. Although separate D/A converter IC's exist on the market today, their extra price makes them prohibitive in cost sensitive embedded control designs. The following application note describes two DAC designs for generation of complex analog waveforms.: (PWM and R-2R Ladder). Both the Pulse Width Modulation (PWM) and resistor ladders require only a few external components to create a D/A converter with the PICmicro™ microcontroller series.

These techniques can be used to generate dual-tone multiplexed frequencies (DTMF) for telephone dialing, controlling the speed of a motor, generating sound and complex waveforms, and generating variable voltages in a power supply.

PULSE WIDTH MODULATION

Pulse Width Modulation (PWM) involves the generation of a series of pulses at a fixed period and frequency. The duty cycle defines the width of each pulse which is varied to generate waveforms. A simple low pass filter is then used to generate an output voltage directly proportional to the average time spent in the HIGH state (i.e., 50% duty cycle is equal to 2.5 volts when V_{DD} = 5.0V).

FIGURE 1: PWM WAVEFORM



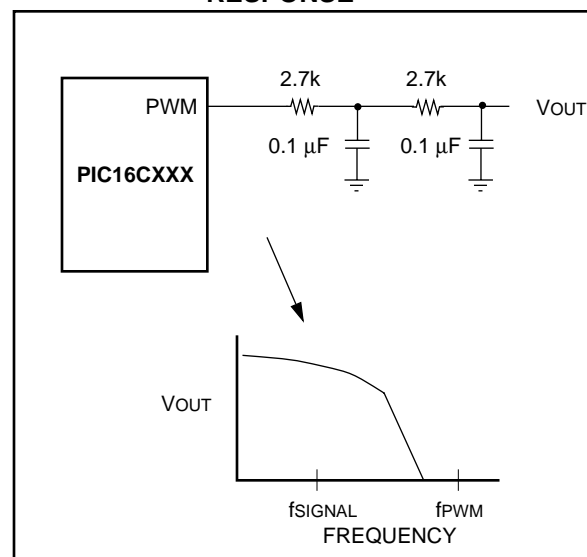
This D/A technique is used to produce slow moving analog outputs (from 0 to 100's of Hz). The software `SINE.ASM`, written for the PIC16C620, produces a 60 Hz sine function at a 5-bit resolution (32 steps). For each step that is generated the software allows ~ 10 PWM cycles for the low pass to settle. The number of PWM cycles for the low pass to settle varies from

one application to another. The designer should experiment with this value to find the most optimal number for the application. These two criteria (sine frequency and # of steps) lead to the required PWM frequency:

$$\begin{aligned} \text{PWM_Freq} &= (\text{Sine_freq}) \cdot (\# \text{ of steps}) \cdot 10 \\ &= 60 \cdot 32 \cdot 10 \\ &= 19.2 \text{ kHz} \end{aligned}$$

A simple RC low pass filter is the only external component needed to complete the circuit. A two pole filter is used in the example to pass the 60 Hz signal while eliminating the step (1920 Hz) and the PWM (19 kHz) frequencies.

FIGURE 2: RC FILTER FREQUENCY RESPONSE



For this application note a software implementation was used to generate the PWM due to its inherent lower cost. If greater resolution or frequency is required, a PICmicro family microcontroller with a hardware PWM should be used.

The TMR0 interrupt is used to generate precise PWM transitions. The time to service this interrupt will limit the minimum and maximum duty cycle for the PWM and hence the min/max voltage that can be produced. Therefore the interrupt service routine has been written to use as few cycles as possible.

A table lookup technique is used to generate one period of a sine function. Other waveforms, such as DC voltage ramps, triangles, sounds etc., can be produced

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from this technique as well. The number of table entries is equal to the resolution required. The designer should carefully investigate the tradeoffs between PWM frequency, RC settling time, waveform resolution, and waveform frequency.

SINE.ASM SOURCE CODE

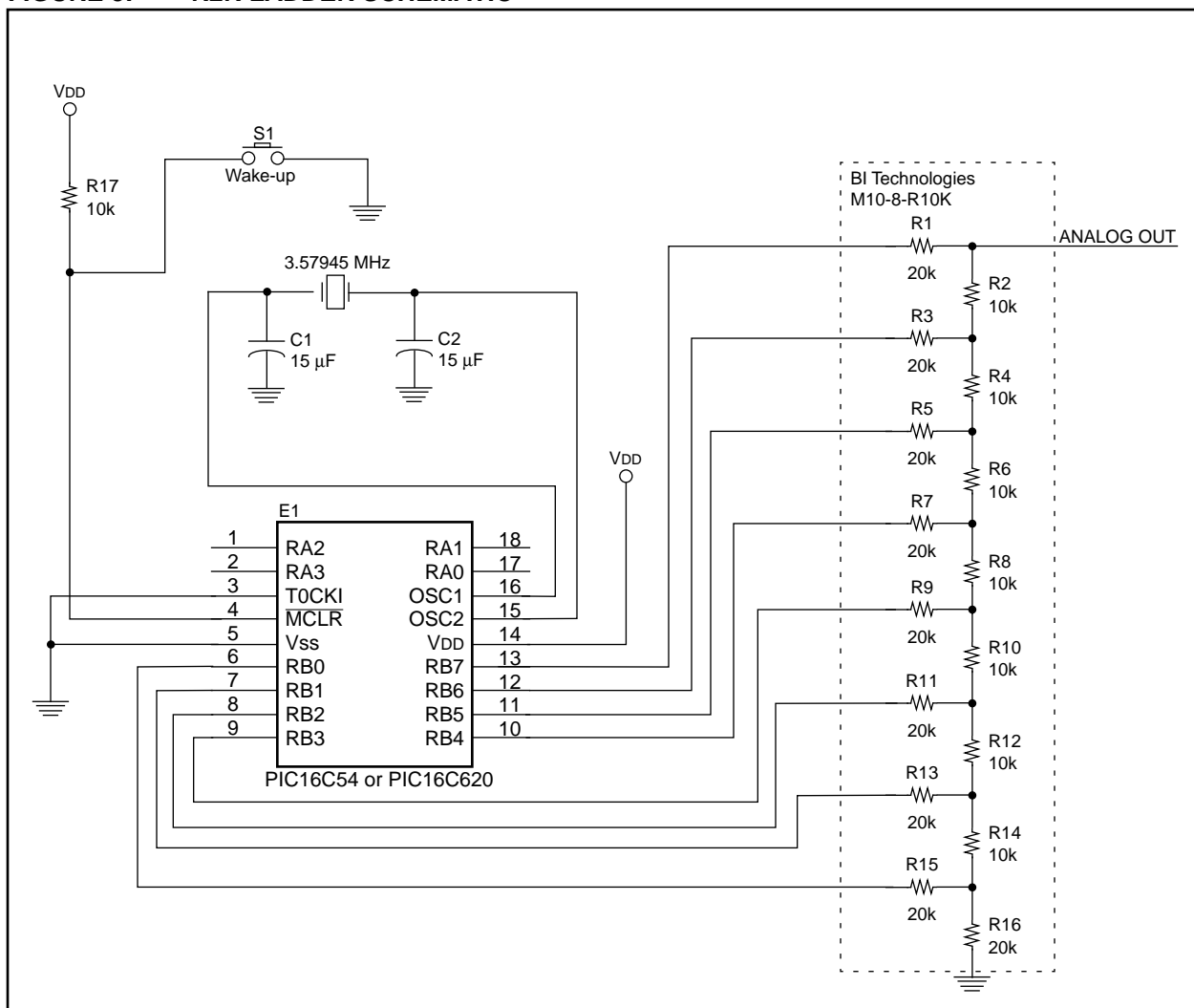
The `SINE.ASM` code example consists of four major code segments:

1. A main routine for counting and timing the 32 steps of the sine wave.
2. The `SetPWM` subroutine to pass a new PWM high and low counter value to the interrupt service routine at each step transition.
3. A table lookup to hold the 32 separate steps for the sine wave.
4. An interrupt service routine which creates the precise timing for the high and low PWM cycles.

R-2R LADDER

Many D/A converters are constructed with an internal resistor network driven by digital output drivers. The resistors are wired in a ladder fashion, with resistors of the same value being used for the rails, and resistors with 2x that value being used for the digital port outputs. Figure 3 shows the connection of a R2R ladder.

FIGURE 3: R2R LADDER SCHEMATIC



Implementation of a R2R ladder can be very inexpensive. BI Technologies sells a single SIP package for 8-bit and 10-bit R2R ladder networks. 8-bit R2R networks can also be manually constructed using 16 discrete resistors. Either way, R2R ladder networks have low EMI emissions, and reduced high frequency harmonics, eliminating the need for a low pass filter in most designs.

Microchip's microcontrollers have I/O pins with very low drive impedance (<75 Ohms at 5V) for both driving logic '1' and '0'. This allows direct connection to the R2R ladder without any external transistor drivers. To achieve 1 LSb accuracy using an 8-bit D/A, it is important to select resistors whose source impedance (in this case, 20k) is ≥ 256 times the driver source impedance.

To test the linearity of this design a +5V power supply was used. Each bit pattern was selected, then the output voltage was measured. The results show the transfer function in Figure 4.

SINE WAVE FUNCTIONS

The simplest way to generate sine waves is through a lookup table. One simply needs to determine the maximum allowable distortion along with the maximum operating frequency. Using these two criteria, the number of sample points needed can be determined:

$$\text{Sample points} = 100 / (\% \text{ allowable voltage step inaccuracy})$$

$$\text{Sample time} = (\text{Sample Points}) \cdot (\text{Frequency})$$

Example:

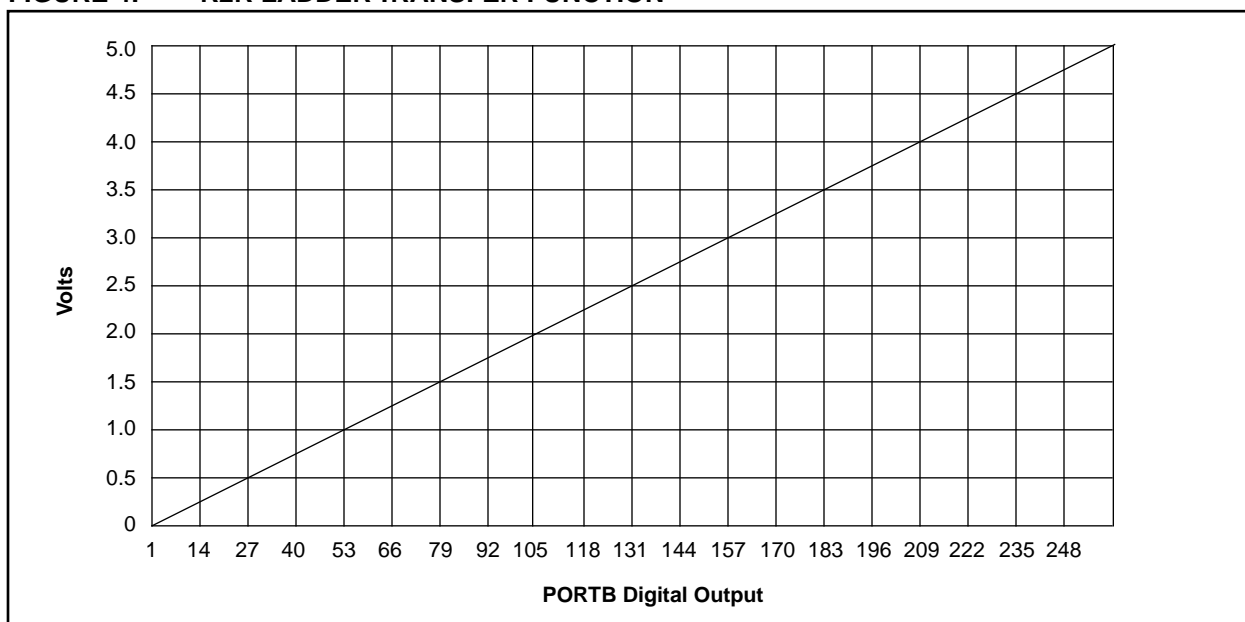
2 kHz Sine wave, <8% voltage step inaccuracy

$$\text{Sample points} = 100/8 = 12.5 \approx 13 \text{ points}$$

$$\text{Sample time} = 13 \cdot 2,000 = 26,000 \text{ ns} = 26 \mu\text{s}$$

To generate a single sine wave, the user simply needs to create a lookup table with the correct number of sample points. Next the software steps through each sample point and moves this value to the PORT output register, sending the correct voltage out of the R2R ladder. It is critical to ensure that the every sample point value be moved to the port output register using the same timing interval.

FIGURE 4: R2R LADDER TRANSFER FUNCTION



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DTMF GENERATION

Many telecom applications, such as auto dialers, telephone keypads and security systems, require DTMF transmission for dialing and data transmission. Using the R2R ladder and seven sine lookup tables, an entire 12-key keypad of DTMF patterns can be generated with a 3.579545 MHz color burst crystal.

The DTMF standard was originally developed by Bell Labs for use by AT&T in telephone systems. There are several specifications that have fallen out of the original standard which come from AT&T, CEPT, CCITT, etc.. The variations from one standard to another are typically deviations in frequency tolerance, power, power difference between two tones, and speech immunity. The CCITT standard is located in Recommendations Q.23 and Q.24 in Section 4.3 of the CCITT Red Book, Volume VI, Fascicle VI.1. The other standards are listed in the References section at the end of this chapter.

A telephone keypad is broken up into 4 rows and 3 columns for a total of 12 keys. Each row and column is represented by a frequency; therefore, each key is uniquely represented by the sum of a row and column as follows:

TABLE 1: 12-KEY KEYPAD FREQUENCY

	1209	1336	1477
697	1	2	3
770	4	5	6
852	7	8	9
941	*	0	#

As an example, the '1' key is represented by a tone of 697 and 1209 Hz simultaneously.

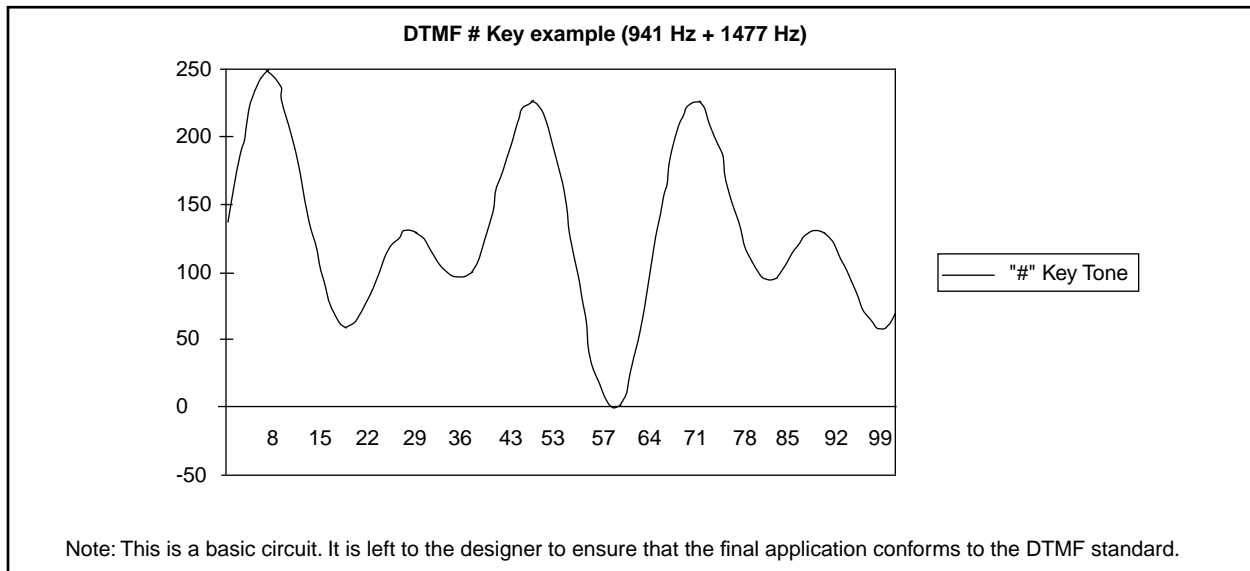
DTMF.ASM SOURCE CODE EXAMPLE

The source code `DTMF.ASM` shows how to generate the complete DTMF table for all keys. The complete DTMF generation algorithm requires only 285 words of code space, including all 7 sine lookup tables. The first 220 words of code space is used for the 7 sine lookup tables. Each sine wave lookup table ends with a value of 127 decimal to show the end of the sine wave pattern. The next section contains a look-up table for each key number which is used to look-up the sine wave pattern frequency number.

The `senddtmf` routine is used to beep the DTMF for 320 ms. Prior to calling the `senddtmf` routine, the key's number is loaded into the `W` register. The sine wave addresses for that key are first calculated and the `WAVEABASE` and `WAVEBBASE` registers are loaded with the sine addresses. Next, each sine wave sample point is looked up and the sum of the two sine waves is moved to `PORTB`. Lastly, the pointer is reset to the sine base address if the value is equal to 127 decimal.

The test program loads each key into `W` and then calls `senddtmf`, showing all possible key patterns. The following figure shows a trace of the # key tones:

FIGURE 5: DTMF # KEY EXAMPLE



CONCLUSION

Using either PWM or R-2R ladder design techniques, many PICmicro microcontroller embedded designs will benefit from their low cost and component count. The following table compares the characteristics of the software and hardware PWM, R-2R ladder and external DAC design alternatives and their respective advantages and disadvantages.

TABLE 2: COST / PERFORMANCE TRADEOFF CHART

Cost / Performance Tradeoffs				
	S/W PWM	H/W PWM	R2R Ladder	External DAC
Cost	Low	Medium	Low	High
# of External Components	Low ⁽¹⁾	Low ⁽¹⁾	Low/Medium ⁽²⁾	Low
I/Os Required	One	One	Eight ⁽³⁾	Two/Nine ⁽⁴⁾
Accuracy	Good ⁽⁵⁾	Good ⁽⁵⁾	Good ⁽⁶⁾	Good/Excellent ⁽⁷⁾
Resolution	Excellent ⁽⁸⁾	Excellent ⁽⁸⁾	Excellent ⁽⁹⁾	Excellent ⁽⁹⁾
Bandwidth	Low ⁽¹⁰⁾	Low/Medium ⁽¹⁰⁾	High	High
Harmonic Distortion	High	Medium	Low	Low

Note 1: One capacitor and one resistor for the low pass filter.

2: Multiply the required resolution times two for the number of external resistors or purchase one resistor SIP (16 resistors are required for 8-bit resolution).

3: The number of I/O's are directly proportional to resolution (8 I/O's for 8-bit resolution).

4: Separate DAC IC's are available with serial or parallel communication.

5: Absolute accuracy is dependent upon supply voltage.

6: Absolute accuracy is dependent upon supply voltage and resistor ladder tolerance.

7: Depends upon D/A reference source (supply voltage or a separate voltage reference).

8: Resolution is a dependent upon the PWM resolution.

9: Resolution is dependent upon the number of resistors in the ladder.

10: The waveform bandwidth is limited by the maximum PWM frequency and the settling time for the low pass filter. For an 8-bit resolution PWM the maximum frequency of operation is 19.5 kHz for a software PWM, and 80 kHz for a hardware PWM.

REFERENCE

Paul Horowitz and Winfield Hill:

"The Art of Electronics",

Cambridge University Press, New York 1989.

Contains an excellent practical description of analog filter design (as well as numerous other useful electronic subjects).

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Please check the Microchip BBS for the latest version of the source code. Microchip's Worldwide Web Address: www.microchip.com; Bulletin Board Support: MCHIPBBS using CompuServe® (CompuServe membership not required).

APPENDIX A: DTMP.ASM

MPASM 01.40.01 Intermediate DTMF.ASM 3-31-1997 11:00:08 PAGE 1

```
LOC OBJECT CODE      LINE SOURCE TEXT
VALUE

00001 ; Filename: DTMF.ASM
00002 ; *****
00003 ; * Author:   John Day *
00004 ; *         Sr. Field Applications Engineer *
00005 ; *         Microchip Technology *
00006 ; * Revision: 1.1 *
00007 ; * Date    December 20, 1995 *
00008 ; * Part:   PIC16C54 *
00009 ; * Compiled using MPASM V1.40 *
00010 ; *****
00011 ; * Include files: *
00012 ; *         NONE (used by DTMF.ASM) *
00013 ; *****
00014 ; * Fuses:   OSC: XT (3.579545 Mhz xtal) *
00015 ; *         WDT: OFF *
00016 ; *         CP: OFF *
00017 ; *****
00018 ; * This program uses an external R2R ladder network to generate complete *
00019 ; * DTMF dial tones used for telephone dialing. *
00020 ; *****
00021 ; * Program Memory: *
00022 ; *         220 Words - sine wave look-up table (7 sine waves total) *
00023 ; *         25 Words - keypad sine address matrix look-up *
00024 ; *         37 Words - DTMF sine wave base initialization/generation *
00025 ; *         3 Words - Initialization *
00026 ; *         25 Words - Test sample code *
00027 ; * RAM Memory: *
00028 ; *         8 Bytes *
00029 ; *****
00030 list      p=16C54, r=dec
00031 #include <p16c5x.inc>
00001 LIST
00002 ; P16C5X.INC Standard Header File, Version 3.30 Microchip Technology, Inc.
00224 LIST
00FF9 00FF9 00032 __CONFIG _XT_OSC&_WDT_OFF&_CP_OFF
00033
00000010 00034 WAVEABASE EQU 10h ; Base address of sine A waveform
00000011 00035 POINTERA EQU 11h ; Pointer to current position in sine A
00000012 00036 WAVEBBASE EQU 12h ; Base address of sine B waveform
00000013 00037 POINTERB EQU 13h ; Pointer to current position in sine B
00000014 00038 NEXTVALUE EQU 14h ; Sum register to store Sine A + Sine B
00000015 00039 SINECOUNT EQU 15h ; LSB counter for time to output DTMF
00000016 00040 SINECOUNTH EQU 16h ; MSB counter for time to output DTMF
00000017 00041 TEMP EQU 17h ; Temporary storage
0000007F 00042 ENDSINE EQU .127 ; Value to show the end of a sine table
00043 ; *****
00044 ; * sinelookup *
00045 ; * This is the look-up table for the (4x3) keypad matrix sine wave table *
00046 ; * There are (7) sine waves stored here and adding any two from the *
00047 ; * matrix will product a DTMF signal for the appropriate key *
00048 ; * Crystal Frequency: 3.579545 Mhz *
00049 ; * Instructions/Loop: 35 *
00050 ; * Base Frequency: 1209 1336 1477 697 770 852 941 Hz *
00051 ; * Actual Frequency: 1217 1345 1475 691 774 852 946 Hz *
```

```

00052 ; * Error          0.7  0.7 -0.1 -0.9  0.5   0  0.5 %      *
00053 ; * Num Table Entries:  21  19  52  37  33  30  27      *
00054 ; * Total Table Entries: 219      *
00055 ; * Program Memory:      *
00056 ; *          220 Words - Used for (7) sine look-up entries      *
00057 ; * RAM Memory:      *
00058 ; *          NONE - Look-up table only      *
00059 ; *****
0000      00060 sinelookup          ; Used as address table to call look-up table
0000 01E2      00061      addwf          PCL,F      ; Add sine offset to PC to jump into table
0001      00062 sineoffset          ; Used to calculate offset value address
0001      00063 sinerowl          ; Address for sine wave in row 1
0001 0895      00064      retlw          149
0002 08AA      00065      retlw          170
0003 08BE      00066      retlw          190
0004 08D0      00067      retlw          208
0005 08E0      00068      retlw          224
0006 08EC      00069      retlw          236
0007 08F6      00070      retlw          246
0008 08FD      00071      retlw          253
0009 08FF      00072      retlw          255
000A 08FE      00073      retlw          254
000B 08FA      00074      retlw          250
000C 08F2      00075      retlw          242
000D 08E6      00076      retlw          230
000E 08D8      00077      retlw          216
000F 08C7      00078      retlw          199
0010 08B4      00079      retlw          180
0011 08A0      00080      retlw          160
0012 088A      00081      retlw          138
0013 0875      00082      retlw          117
0014 085F      00083      retlw          95
0015 084B      00084      retlw          75
0016 0838      00085      retlw          56
0017 0827      00086      retlw          39
0018 0819      00087      retlw          25
0019 080D      00088      retlw          13
001A 0805      00089      retlw          5
001B 0801      00090      retlw          1
001C 0800      00091      retlw          0
001D 0802      00092      retlw          2
001E 0809      00093      retlw          9
001F 0813      00094      retlw          19
0020 081F      00095      retlw          31
0021 082F      00096      retlw          47
0022 0841      00097      retlw          65
0023 0855      00098      retlw          85
0024 086A      00099      retlw          106
0025 087F      00100      retlw          127      ; End of this sine wave
0026      00101 sinerow2          ; Address for sine wave in row 2
0026 0898      00102      retlw          152
0027 08AF      00103      retlw          175
0028 08C5      00104      retlw          197
0029 08D8      00105      retlw          216
002A 08E8      00106      retlw          232
002B 08F4      00107      retlw          244
002C 08FC      00108      retlw          252
002D 08FF      00109      retlw          255
002E 08FE      00110      retlw          254
002F 08F8      00111      retlw          248
0030 08EE      00112      retlw          238
0031 08E0      00113      retlw          224
0032 08CF      00114      retlw          207
0033 08BA      00115      retlw          186
0034 08A4      00116      retlw          164
0035 088C      00117      retlw          140

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```
0036 0873      00118      retlw      115
0037 085B      00119      retlw      91
0038 0845      00120      retlw      69
0039 0830      00121      retlw      48
003A 081F      00122      retlw      31
003B 0811      00123      retlw      17
003C 0807      00124      retlw      7
003D 0801      00125      retlw      1
003E 0800      00126      retlw      0
003F 0803      00127      retlw      3
0040 080B      00128      retlw      11
0041 0817      00129      retlw      23
0042 0827      00130      retlw      39
0043 083A      00131      retlw      58
0044 0850      00132      retlw      80
0045 0867      00133      retlw     103
0046 087F      00134      retlw     127      ; End of this sine wave
0047          00135 sinerow3      ; Address for sine wave in row 3
0047 089A      00136      retlw     154
0048 08B4      00137      retlw     180
0049 08CB      00138      retlw     203
004A 08DF      00139      retlw     223
004B 08EE      00140      retlw     238
004C 08F9      00141      retlw     249
004D 08FF      00142      retlw     255
004E 08FF      00143      retlw     255
004F 08F9      00144      retlw     249
0050 08EE      00145      retlw     238
0051 08DF      00146      retlw     223
0052 08CB      00147      retlw     203
0053 08B4      00148      retlw     180
0054 089A      00149      retlw     154
0055 0880      00150      retlw     128
0056 0865      00151      retlw     101
0057 084B      00152      retlw      75
0058 0834      00153      retlw      52
0059 0820      00154      retlw      32
005A 0811      00155      retlw      17
005B 0806      00156      retlw       6
005C 0800      00157      retlw       0
005D 0800      00158      retlw       0
005E 0806      00159      retlw       6
005F 0811      00160      retlw      17
0060 0820      00161      retlw      32
0061 0834      00162      retlw      52
0062 084B      00163      retlw      75
0063 0865      00164      retlw     101
0064 087F      00165      retlw     127      ; End of this sine wave
0065          00166 sinerow4      ; Address for sine wave in row 4
0065 089D      00167      retlw     157
0066 08B9      00168      retlw     185
0067 08D2      00169      retlw     210
0068 08E6      00170      retlw     230
0069 08F5      00171      retlw     245
006A 08FE      00172      retlw     254
006B 08FF      00173      retlw     255
006C 08FA      00174      retlw     250
006D 08EE      00175      retlw     238
006E 08DD      00176      retlw     221
006F 08C6      00177      retlw     198
0070 08AB      00178      retlw     171
0071 088E      00179      retlw     142
0072 0871      00180      retlw     113
0073 0854      00181      retlw      84
0074 0839      00182      retlw      57
0075 0822      00183      retlw      34
```



```

0076 0811    00184    retlw    17
0077 0805    00185    retlw    5
0078 0800    00186    retlw    0
0079 0801    00187    retlw    1
007A 080A    00188    retlw    10
007B 0819    00189    retlw    25
007C 082D    00190    retlw    45
007D 0846    00191    retlw    70
007E 0862    00192    retlw    98
007F 087F    00193    retlw    127    ; End of this sine wave
0080          00194 sinecolumna    ; Address for sine wave in column A
0080 08A5    00195    retlw    165
0081 08C8    00196    retlw    200
0082 08E4    00197    retlw    228
0083 08F7    00198    retlw    247
0084 08FF    00199    retlw    255
0085 08FC    00200    retlw    252
0086 08EE    00201    retlw    238
0087 08D7    00202    retlw    215
0088 08B7    00203    retlw    183
0089 0893    00204    retlw    147
008A 086C    00205    retlw    108
008B 0848    00206    retlw    72
008C 0828    00207    retlw    40
008D 0811    00208    retlw    17
008E 0803    00209    retlw    3
008F 0800    00210    retlw    0
0090 0808    00211    retlw    8
0091 081B    00212    retlw    27
0092 0837    00213    retlw    55
0093 085A    00214    retlw    90
0094 087F    00215    retlw    127    ; End of this sine wave
0095          00216 sinecolumnb    ; Address for sine wave in column B
0095 08A9    00217    retlw    169
0096 08CE    00218    retlw    206
0097 08EB    00219    retlw    235
0098 08FC    00220    retlw    252
0099 08FF    00221    retlw    255
009A 08F5    00222    retlw    245
009B 08DE    00223    retlw    222
009C 08BC    00224    retlw    188
009D 0895    00225    retlw    149
009E 086A    00226    retlw    106
009F 0843    00227    retlw    67
00A0 0821    00228    retlw    33
00A1 080A    00229    retlw    10
00A2 0800    00230    retlw    0
00A3 0803    00231    retlw    3
00A4 0814    00232    retlw    20
00A5 0831    00233    retlw    49
00A6 0856    00234    retlw    86
00A7 087F    00235    retlw    127    ; End of this sine wave
00A8          00236 sinecolumnc    ; Address for sine wave in column C (double sine wave)
00A8 08AD    00237    retlw    173
00A9 08D4    00238    retlw    212
00AA 08F1    00239    retlw    241
00AB 08FF    00240    retlw    255
00AC 08FC    00241    retlw    252
00AD 08E9    00242    retlw    233
00AE 08C8    00243    retlw    200
00AF 089E    00244    retlw    158
00B0 0870    00245    retlw    112
00B1 0844    00246    retlw    68
00B2 0820    00247    retlw    32
00B3 0808    00248    retlw    8
00B4 0800    00249    retlw    0

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```
00B5 0808    00250    retlw    8
00B6 0820    00251    retlw    32
00B7 0844    00252    retlw    68
00B8 0870    00253    retlw   112
00B9 089E    00254    retlw   158
00BA 08C8    00255    retlw   200
00BB 08E9    00256    retlw   233
00BC 08FC    00257    retlw   252
00BD 08FF    00258    retlw   255
00BE 08F1    00259    retlw   241
00BF 08D4    00260    retlw   212
00C0 08AD    00261    retlw   173
00C1 0880    00262    retlw   128
00C2 0852    00263    retlw    82
00C3 082B    00264    retlw    43
00C4 080E    00265    retlw    14
00C5 0800    00266    retlw     0
00C6 0803    00267    retlw     3
00C7 0816    00268    retlw    22
00C8 0837    00269    retlw    55
00C9 0861    00270    retlw    97
00CA 088F    00271    retlw   143
00CB 08BB    00272    retlw   187
00CC 08DF    00273    retlw   223
00CD 08F7    00274    retlw   247
00CE 08FF    00275    retlw   255
00CF 08F7    00276    retlw   247
00D0 08DF    00277    retlw   223
00D1 08BB    00278    retlw   187
00D2 088F    00279    retlw   143
00D3 0861    00280    retlw    97
00D4 0837    00281    retlw    55
00D5 0816    00282    retlw    22
00D6 0803    00283    retlw     3
00D7 0800    00284    retlw     0
00D8 080E    00285    retlw    14
00D9 082B    00286    retlw    43
00DA 0852    00287    retlw    82
00DB 087F    00288    retlw   127          ; End of this sine wave
00289 ; *****
00290 ; * sineaddress
00291 ; * This subroutine is used to calculate actual address in the sinelookup
00292 ; * table for two DTMF waveforms. It is only called by setdtmfbase. W
00293 ; * is loaded with the key number and this routine returns the sine
00294 ; * lookup address the sine waves.
00295 ; * RAM used: W
00296 ; * PROGRAM MEM: 25 Words
00297 ; *****
00DC 00298 sineaddress ; Lookup table for sine address
00DC 01E2 00299 addwf PCL,F ; Add to PC to jump into table
00DD 00300 keyoffset
00DD 0800 00301 k1 retlw sinerow1-sineoffset ; Offset for Row 1 sine wave
00DE 087F 00302 retlw sinecolumna-sineoffset ; Offset for Column A sine wave
00DF 0800 00303 k2 retlw sinerow1-sineoffset ; Offset for Row 1 sine wave
00E0 0894 00304 retlw sinecolumnb-sineoffset ; Offset for Column A sine wave
00E1 0800 00305 k3 retlw sinerow1-sineoffset ; Offset for Row 1 sine wave
00E2 08A7 00306 retlw sinecolumnc-sineoffset ; Offset for Column A sine wave
00E3 0825 00307 k4 retlw sinerow2-sineoffset ; Offset for Row 2 sine wave
00E4 087F 00308 retlw sinecolumna-sineoffset ; Offset for Column A sine wave
00E5 0825 00309 k5 retlw sinerow2-sineoffset ; Offset for Row 2 sine wave
00E6 0894 00310 retlw sinecolumnb-sineoffset ; Offset for Column B sine wave
00E7 0825 00311 k6 retlw sinerow2-sineoffset ; Offset for Row 2 sine wave
00E8 08A7 00312 retlw sinecolumnc-sineoffset ; Offset for Column B sine wave
00E9 0846 00313 k7 retlw sinerow3-sineoffset ; Offset for Row 3 sine wave
00EA 087F 00314 retlw sinecolumna-sineoffset ; Offset for Column B sine wave
00EB 0846 00315 k8 retlw sinerow3-sineoffset ; Offset for Row 3 sine wave
```

```

00EC 0894    00316    retlw    sinecolumnb-sineoffset    ; Offset for Column B sine wave
00ED 0846    00317 k9    retlw    sinerow3-sineoffset        ; Offset for Row 3 sine wave
00EE 08A7    00318    retlw    sinecolumnc-sineoffset    ; Offset for Column C sine wave
00EF 0864    00319 k10   retlw    sinerow4-sineoffset        ; Offset for Row 4 sine wave
00F0 087F    00320    retlw    sinecolumna-sineoffset    ; Offset for Column C sine wave
00F1 0864    00321 k11   retlw    sinerow4-sineoffset        ; Offset for Row 4 sine wave
00F2 0894    00322    retlw    sinecolumnb-sineoffset    ; Offset for Column C sine wave
00F3 0864    00323 k12   retlw    sinerow4-sineoffset        ; Offset for Row 4 sine wave
00F4 08A7    00324    retlw    sinecolumnc-sineoffset    ; Offset for Column C sine wave
00000000    00325 key1=k1-keyoffset            ; Calculation for sine addr for keypad 1
00000002    00326 key2=k2-keyoffset            ; Calculation for sine addr for keypad 2
00000004    00327 key3=k3-keyoffset            ; Calculation for sine addr for keypad 3
00000006    00328 key4=k4-keyoffset            ; Calculation for sine addr for keypad 4
00000008    00329 key5=k5-keyoffset            ; Calculation for sine addr for keypad 5
0000000A    00330 key6=k6-keyoffset            ; Calculation for sine addr for keypad 6
0000000C    00331 key7=k7-keyoffset            ; Calculation for sine addr for keypad 7
0000000E    00332 key8=k8-keyoffset            ; Calculation for sine addr for keypad 8
00000010    00333 key9=k9-keyoffset            ; Calculation for sine addr for keypad 9
00000012    00334 keystar=k10-keyoffset        ; Calculation for sine addr for keypad *
00000014    00335 key0=k11-keyoffset           ; Calculation for sine addr for keypad 0
00000016    00336 keypound=k12-keyoffset        ; Calculation for sine addr for keypad #
00337 ; *****
00338 ; * senddtmf                                     *
00339 ; * This subroutine is used to calculate the offset address for          *
00340 ; * the two sine waves to be sent and initialize the WAVEABASE and WAVEBBASE*
00341 ; * file registers. The key number (key0 - key9 or keystar or keypound) is *
00342 ; * loaded into W before this routine is called. Next, the DTMF for that  *
00343 ; * key is sent to the R2R ladder through portB for 320 mS              *
00344 ; * Example:                                     *
00345 ; * movlw    key1                                  *
00346 ; * call    senddtmf                              *
00347 ; * RAM used:      8 bytes                          *
00348 ; * PROGRAM MEM:  37 Words                         *
00349 ; *****
00F5    00350 senddtmf
00F5 0037    00351    movwf    TEMP            ; Initialize temp with key number
00F6 09DC    00352    call    sineaddress      ; Get the addr for sine wave a for this key
00F7 0030    00353    movwf    WAVEABASE       ; Initialize sine wave A base address
00F8 03B0    00354    swapf    WAVEABASE,F     ; swap WAVEABASE so that Z bit is not affected
00F9 0031    00355    movwf    POINTERA        ; Initialize sine wave A pointer address
00FA 0297    00356    incf    TEMP,W           ; Now we get the second sine wave address...
00FB 09DC    00357    call    sineaddress      ; Get the addr for sine wave b for this key
00FC 0032    00358    movwf    WAVEBBASE       ; Initialize sine wave B base address
00FD 03B2    00359    swapf    WAVEBBASE,F     ; swap WAVEBBASE so that Z bit is not affected
00FE 0033    00360    movwf    POINTERB        ; Initialize sine wave B pointer address
00FF 0C20    00361    movlw    20h             ; Place 32 decimal into W for loop counter
0100 0036    00362    movwf    SINECOUNTH      ; Initialize loop counter to 20
0101    00363 loopsine2cyc
0101 0B02    00364    goto    loopsine        ; Waste two cycles to maintain 35 cycle loop count
0102    00365 loopsine
0102 0211    00366    movf    POINTERA,W       ; Place sine wave address into W
0103 0900    00367    call    sinelookup       ; Lookup first sine wave
0104 0034    00368    movwf    NEXTVALUE       ; Place first sine wave into NEXTVALUE
0105 0F7F    00369    xorlw    ENDSINE         ; Update Z bit
0106 0390    00370    swapf    WAVEABASE,W     ; Restore to beginning of sine wave
0107 0643    00371    btfs    STATUS,Z         ; Skip if not at end of sine wave
0108 0031    00372    movwf    POINTERA        ; Restore start address if at end of sine
0109 02B1    00373    incf    POINTERA,F       ; Move to the next place in the wave
010A 0213    00374    movf    POINTERB,W       ; Place sine wave address into W
010B 0900    00375    call    sinelookup       ; Lookup second sine wave
010C 01F4    00376    addwf    NEXTVALUE,F     ; Add second sine wave into NEXTVALUE
010D 0F7F    00377    xorlw    ENDSINE         ; Update Z bit
010E 0392    00378    swapf    WAVEBBASE,W     ; Pointer of sine wave beginning -> W
010F 0643    00379    btfs    STATUS,Z         ; Skip if not at end of sine wave
0110 0033    00380    movwf    POINTERB        ; Restore start address if at end of sine
0111 02B3    00381    incf    POINTERB,F       ; Move to next place in the wave

```

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```
0112 0314    00382      rrf      NEXTVALUE,W      ; Divide by 2, Place output into PORTB
0113 0026    00383      movwf   PORTB      ; Update PORTB with new R2R value
0114 0B15    00384      goto   waste2cyc   ; Waste (2) cycles for 35 total
0115                    00385 waste2cyc
0115 02F5    00386      decfsz SINECOUNT,F ; Skip if we are done
0116 0B01    00387      goto   loopsine2cyc ; Do it again! (add 2 cycles as well)
0117 02F6    00388      decfsz SINECOUNTH,F ; Skip if we are done
0118 0B02    00389      goto   loopsine    ; Do it again!
0119 0800    00390      retlw  0           ; Return from sine output
00391 ; *****
00392 ; * init
00393 ; * This code is used to initialize the PIC. PORTB is set to zero and all
00394 ; * pins are set to outputs
00395 ; * RAM used:      0 bytes
00396 ; * PROGRAM MEM:   3 Words
00397 ; *****
011A                    00398 init
011A 0066    00399      clrf   PORTB      ; Init output latches for port B to 0
011B 0040    00400      clrw   ; Clear W register
011C 0006    00401      tris   PORTB      ; Set all of PORT B to outputs
00402 ; *****
00403 ; * testallkeys
00404 ; * This code is used to test all possible keys in the keypad. First each
00405 ; * key address is loaded and then senddtmf is called.
00406 ; * RAM used:      0 bytes
00407 ; * PROGRAM MEM:   25 Words
00408 ; *****
011D                    00409 testallkeys
011D 0C00    00410      movlw  key1       ; Place key "1" address into W
011E 09F5    00411      call   senddtmf   ; Transmit DTMF tone for this key
011F 0C02    00412      movlw  key2       ; Place key "2" address into W
0120 09F5    00413      call   senddtmf   ; Transmit DTMF tone for this key
0121 0C04    00414      movlw  key3       ; Place key "3" address into W
0122 09F5    00415      call   senddtmf   ; Transmit DTMF tone for this key
0123 0C06    00416      movlw  key4       ; Place key "4" address into W
0124 09F5    00417      call   senddtmf   ; Transmit DTMF tone for this key
0125 0C08    00418      movlw  key5       ; Place key "5" address into W
0126 09F5    00419      call   senddtmf   ; Transmit DTMF tone for this key
0127 0C0A    00420      movlw  key6       ; Place key "6" address into W
0128 09F5    00421      call   senddtmf   ; Transmit DTMF tone for this key
0129 0C0C    00422      movlw  key7       ; Place key "7" address into W
012A 09F5    00423      call   senddtmf   ; Transmit DTMF tone for this key
012B 0C0E    00424      movlw  key8       ; Place key "8" address into W
012C 09F5    00425      call   senddtmf   ; Transmit DTMF tone for this key
012D 0C10    00426      movlw  key9       ; Place key "9" address into W
012E 09F5    00427      call   senddtmf   ; Transmit DTMF tone for this key
012F 0C12    00428      movlw  keystar    ; Place key "*" address into W
0130 09F5    00429      call   senddtmf   ; Transmit DTMF tone for this key
0131 0C14    00430      movlw  key0       ; Place key "0" address into W
0132 09F5    00431      call   senddtmf   ; Transmit DTMF tone for this key
0133 0C16    00432      movlw  keypound   ; Place key "#" address into W
0134 09F5    00433      call   senddtmf   ; Transmit DTMF tone for this key
0135 0B1D    00434      goto   testallkeys ; jump back and do it again!
0136                    00435 resetvector
01FF                    00436      ORG    1ffh       ; The RESET vector of a 54 is at 1FFh
01FF 0B1A    00437      goto   init       ; Jump to initialion routine
00438                    END
```

MEMORY USAGE MAP ('X' = Used, '-' = Unused)

```
0000 : XXXXXXXXXXXXXXXXXXXX XXXXXXXXXXXXXXXXXXXX XXXXXXXXXXXXXXXXXXXX XXXXXXXXXXXXXXXXXXXX
0040 : XXXXXXXXXXXXXXXXXXXX XXXXXXXXXXXXXXXXXXXX XXXXXXXXXXXXXXXXXXXX XXXXXXXXXXXXXXXXXXXX
0080 : XXXXXXXXXXXXXXXXXXXX XXXXXXXXXXXXXXXXXXXX XXXXXXXXXXXXXXXXXXXX XXXXXXXXXXXXXXXXXXXX
00C0 : XXXXXXXXXXXXXXXXXXXX XXXXXXXXXXXXXXXXXXXX XXXXXXXXXXXXXXXXXXXX XXXXXXXXXXXXXXXXXXXX
0100 : XXXXXXXXXXXXXXXXXXXX XXXXXXXXXXXXXXXXXXXX XXXXXXXXXXXXXXXXXXXX XXXXXXXX-----
01C0 : -----X
0FC0 : -----X
```

All other memory blocks unused.

Program Memory Words Used: 311
Program Memory Words Free: 201

Errors : 0
Warnings : 0 reported, 0 suppressed
Messages : 0 reported, 0 suppressed

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Please check the Microchip BBS for the latest version of the source code. Microchip's Worldwide Web Address: www.microchip.com; Bulletin Board Support: MCHIPBBS using CompuServe® (CompuServe membership not required).

APPENDIX B: SINE.ASM

MPASM 01.40.01 Intermediate SINE.ASM 3-31-1997 10:59:22 PAGE 1

```
LOC OBJECT CODE      LINE SOURCE TEXT
VALUE

00001 ;*****
00002      TITLE "PWM based sine wave generator"
00003      LIST P=16C620, R=DEC
00004
00005      INCLUDE      <P16C620.INC>
00001      LIST
00002 ; P16C620.INC Standard Header File, Version 1.01 Microchip Technology, Inc.
00164      LIST
2007 3FB1 00006      __CONFIG      _BODEN_OFF&_CP_OFF&_PWRTE_ON&_WDT_OFF&_XT_OSC
00007 ;
00008 ;*****
00009 ;      File:          SINE.ASM
00010 ;      Author:        Rob Stein
00011 ;      Date:          12/20/95
00012 ;      Assembler:    MPASM V01.40
00013 ;      Xtal:         20 Mhz
00014 ;      Inst Clk:    5 Mhz (200nSec)
00015 ;*****
00016 ;      Description:
00017 ;      Outputs a 60 Hz synthesized sine wave (32 step) via a general
00018 ;      purpose I/O pin (RB1) into a low pass filter. A software PWM
00019 ;      routine is used to create 32 separate sinewave steps. This
00020 ;      software was prototyped with the PICDEM1 board.
00021 ;
00022 ;      Circuit Diagram:
00023 ;
00024 ;
00025 ;      RB1  ___/\      /\      /\      /\      /\      /\      Analog Output
00026 ;              \/\      \/\      \/\      \/\      \/\      \/\
00027 ;
00028 ;              ----- 0.1uF      ----- 0.1uF
00029 ;              -----
00030 ;              |                      |
00031 ;              GND                    GND
00032 ;
00033 ;      ROM Usage: 98 words
00034 ;
00035 ;      RAM Usage: 6 bytes
00036 ;
00037 ;***** Constant Definition *****
00038
01312D00 00039 FXTAL      EQU      .20000000      ; Crystal Frequency
004C4B40 00040 FINST      EQU      FXTAL/4      ; Instruction Cycle Frequency
0000003C 00041 FSINE      EQU      .60          ; Sine function frequency
00000020 00042 STEP#      EQU      .32          ; Number of steps
00000780 00043 FSTEP      EQU      FSINE * STEP# ; Step frequency
00044
00045 ;***** Register Definition *****
00046
00000020 00047 TEMPW      EQU      0x20          ; Temporary interrupt storage for W
00000021 00048 DELAYCNT1   EQU      0x21          ; Delay routine counter low
00000022 00049 DELAYCNT2   EQU      0x22          ; Delay routine counter high
00000023 00050 STEPCOUNT   EQU      0x23          ; Sine step counter
00000024 00051 OUTLOW      EQU      0x24          ; PWM low cycle load for TMR0
```

```

00000025    00052 OUTHIGH EQU    0x25          ; PWM high cycle load for TMR0
00053
00054 ;*****
00055
00000001    00056 PWM    EQU    0x01          ; RB1 used for PWM output
00057
00058 ;*****
00059 ;
00060 ;*****
00061
0000        00062          org    0x000
0000 2816    00063          goto   Start          ; Begining of Program
00064
00065 ;*****
00066 ;
00067 ;
00068 ;
00069 ;
00070 ;
00071 ;
00072 ;
00073 ;
00074 ;
00075 ;
00076 ;
00077 ;
00078 ;
00079 ;*****
00080
0004        00081          org    0x004          ; Interrupt vector location
0004        00082 IntVector
0004 00A0    00083          movwf  TEMPW          ; Temporarily save W
0005 1886    00084          btfsc  PORTB,PWM        ; Was this a Low cycle ?
0006 280F    00085          goto   PWMLow          ; No ...
0007        00086 PWMHigh
0007 0E25    00087          swapf  OUTHIGH,W        ; Yes... Load hi-time w/o affecting STATUS flags
0008 1486    00088          bsf    PORTB,PWM
0009 0000    00089          nop
000A 0081    00090          movwf  TMR0            ; Load next edge interrupt time
000B 110B    00091          bcf    INTCON,TOIF     ; Clear TMR0 overflow flag
000C 0EA0    00092          swapf  TEMPW,F        ; Swap saved W
000D 0E20    00093          swapf  TEMPW,W        ; Restore W
000E        00094 IntEndHi
000E 0009    00095          retfie                ; Return from Interrupt
000F        00096 PWMLow
000F 1086    00097          bcf    PORTB,PWM
0010 0E24    00098          swapf  OUTLOW,W        ; Load low time
0011 0081    00099          movwf  TMR0            ; Load next edge interrupt time
0012 110B    00100          bcf    INTCON,TOIF     ; Clear TMR0 overflow flag
0013 0EA0    00101          swapf  TEMPW,F        ; Swap saved W
0014 0E20    00102          swapf  TEMPW,W        ; Restore W
0015        00103 IntEndLo
0015 0009    00104          retfie                ; Return from Interrupt
00105
00106 ;*****
00107 ;
00108 ;*****
00109 Start
0016 0183    00110          clrf   STATUS          ; Intitialize STATUS & select bank 0
0017 1683    00111          bsf    STATUS,RP0      ; Select register bank 1
0018 3088    00112          movlw  0x88
Message[302]: Register in operand not in bank 0.  Ensure that bank bits are correct.
0019 0081    00113          movwf  OPTION_REG      ; 1:1 TMR0 prescaler, PORTB pull-ups disabled
001A 30FF    00114          movlw  0xFF
Message[302]: Register in operand not in bank 0.  Ensure that bank bits are correct.
001B 0085    00115          movwf  TRISA           ; Set Port_A as inputs

```

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```
Message[302]: Register in operand not in bank 0. Ensure that bank bits are correct.
001C 0186 00116      clrf    TRISB      ; Set Port_B as outputs
001D 1283 00117      bcf    STATUS,RP0  ; Select register bank 0
001E 0086 00118      movwf  PORTB      ; PORT_B pins high
001F 0181 00119      clrf    TMR0      ; Initialize TMR0
0020 30A0 00120      movlw  0xA0
0021 008B 00121      movwf  INTCON     ; Enable TMR0 and global interrupt
0022      00122 ResetStep
0022 3020 00123      movlw  STEP#
0023 00A3 00124      movwf  STEPCOUNT  ; Load counter for 32 steps
0024      00125 StepLoop
0024 2059 00126      call   Delay      ; Software delay
0025 0823 00127      movf   STEPCOUNT,W ; Pass table offset via W
0026 2037 00128      call   SineTable  ; Get table value
0027 202B 00129      call   SetPWM     ; Set-up low & high PWM values
0028 0BA3 00130      decfsz STEPCOUNT,F ; Next step
0029 2824 00131      goto   StepLoop
002A 2822 00132      goto   ResetStep
00133
00134 ;*****
00135 ;                               Set PWM Subroutine *
00136 ; The following calculates the next low and high PWM time values. *
00137 ; The two time values, OUTLOW and OUTHIGH, will be passed to the *
00138 ; interrupt service routine. *
00139 ;*****
002B      00140 SetPWM
002B 138B 00141      bcf    INTCON,GIE ; Disable interrupts to protect ISR from...
00142      ; corrupting OUTLOW & OUTHIGH values
002C 00A4 00143      movwf  OUTLOW     ; Set PWM Duty Cycle
002D 0924 00144      comf   OUTLOW,W
00145
002E 3E0A 00146      addlw  IntEndHi-IntVector ; Adjust for Int Service time
002F 00A5 00147      movwf  OUTHIGH
0030 0824 00148      movf   OUTLOW,W
0031 3E0A 00149      addlw  IntEndHi-IntVector ; Adjust for Int Service time
0032 00A4 00150      movwf  OUTLOW
00151
0033 0EA4 00152      swapf  OUTLOW,F    ; Swap nibbles so that interrupt service...
0034 0EA5 00153      swapf  OUTHIGH,F  ; will not corrupt STATUS
0035 178B 00154      bsf    INTCON,GIE ; Re-enable interrupts
0036 0008 00155      return
00156
00157 ;*****
00158 ;                               Lookup Table for Sine Wave
00159 ; This 32 entry table was generated to produce a 0.1*Vdd to
00160 ; 0.9*Vdd (typically 0.5 to 4.5 volt) sine function.
00161 ;*****
0037      00162 SineTable
0037 0782 00163      addwf  PCL,F      ; Increment into table
0038 3400 00164      retlw  .0         ; Dummy table value
0039 3480 00165      retlw  .128      ; 0 degree, 2.5 volt
003A 3494 00166      retlw  .148
003B 34A7 00167      retlw  .167
003C 34B9 00168      retlw  .185
003D 34C8 00169      retlw  .200
003E 34D5 00170      retlw  .213
003F 34DE 00171      retlw  .222
0040 34E4 00172      retlw  .228
0041 34E6 00173      retlw  .230      ; 90 degree, 4.5 volt
0042 34E4 00174      retlw  .228
0043 34DE 00175      retlw  .222
0044 34D5 00176      retlw  .213
0045 34C8 00177      retlw  .200
0046 34B9 00178      retlw  .185
0047 34A7 00179      retlw  .167
```



```

0048 3494      00180      retlw   .148
0049 3480      00181      retlw   .128      ; 180 degree, 2.5 volt
004A 346C      00182      retlw   .108
004B 3459      00183      retlw   .89
004C 3447      00184      retlw   .71
004D 3438      00185      retlw   .56
004E 342B      00186      retlw   .43
004F 3422      00187      retlw   .34
0050 341C      00188      retlw   .28
0051 341A      00189      retlw   .26      ; 270 degree, 0.5 volt
0052 341C      00190      retlw   .28
0053 3422      00191      retlw   .34
0054 342B      00192      retlw   .43
0055 3438      00193      retlw   .56
0056 3447      00194      retlw   .71
0057 3459      00195      retlw   .89
0058 346C      00196      retlw   .108
00197
00198 ;*****
00199 ;
00200 ;           Time Delay Sub-routine
00201 ;           The time delay is used to create the precision 32 steps. The
00202 ;           32 step times totaled together add up to a 60 Hz rate. Note that
00203 ;           constants DELAYCNT# are used so that other frequencies can easily
00204 ;           be generated (example: FSINE equ .50 for a 50 Hz sinewave).
00205 ;*****
00000A2C      00205 TDELAY      EQU      FINST/FSTEP      ; # of delay count cycles
0000032D      00206 ADJTDELAY      EQU      TDELAY/3 - 55      ; Adjust for main routine cycles
00000003      00207 TDELAYHI      EQU      high ADJTDELAY      ; Most Significant Byte of TDELAY
0000002D      00208 TDELAYLO      EQU      low ADJTDELAY      ; Least Sig. Byte of TDELAY
00209
0059          00210 Delay
0059 3003      00211      movlw   TDELAYHI
005A 00A2      00212      movwf   DELAYCNT2      ; Load high byte delay counter
005B 01A1      00213      clrf   DELAYCNT1
005C          00214 LoopD1
005C 0BA1      00215      decfsz DELAYCNT1,F      ; Finished with 256 loops ?
005D 285C      00216      goto   LoopD1          ; No ... keep going
005E 0BA2      00217      decfsz DELAYCNT2,F      ; Yes... Done with TDELAYHI loops ?
005F 285C      00218      goto   LoopD1          ; No ...
00219
0060 302D      00220      movlw   TDELAYLO      ; Yes... Load low byte with adjust for...
0061 00A1      00221      movwf   DELAYCNT1      ; main routine cycles.
0062          00222 LoopD2
0062 0BA1      00223      decfsz DELAYCNT1,F      ; Finished with TDELAYLO loops ?
0063 2862      00224      goto   LoopD2          ; No ... keep going
0064 0008      00225      return      ; Yes... Finished
00226
00227      END          ; That's all Folks !

```

MEMORY USAGE MAP ('X' = Used, '-' = Unused)

```

0000 : X---XXXXXXXXXXXX XXXXXXXXXXXXXXXXXXXX XXXXXXXXXXXXXXXXXXXX XXXXXXXXXXXXXXXXXXXX
0040 : XXXXXXXXXXXXXXXXXXXX XXXXXXXXXXXXXXXXXXXX XXXXX-----
2000 : -----X-----

```

All other memory blocks unused.

```

Program Memory Words Used:   98
Program Memory Words Free:  414

```

```

Errors   :   0
Warnings :   0 reported,   0 suppressed
Messages :   3 reported,   0 suppressed

```

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