Application Report
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Generation of a Sine Wave Using a TMS320C54x Digital Signal Processor

Francis Kua — *Field Applications Engineer, Texas Instruments Singapore*

ABSTRACT

This application report explains how a sine wave can be generated using a TMS320C54x™ digital signal processor (DSP).

The sine wave has found its usage in various applications, including factory testing for connectivity. One method of sine-wave generation is based on a positive feedback system that employs the principle of oscillation. Oscillation can only be achieved if the system satisfies the Bakhausen Criterion. Following the principles of an analog oscillator, a digital oscillator is implemented using a special two-pole bandpass filter. For more information on this subject, refer to *Digital Signal Processing: Principles, Algorithms, and Applications* by John Proakis and Dimitris Manolakis [1]. The filter and the final difference equation are shown in Figure 1 and Equation (1), respectively.

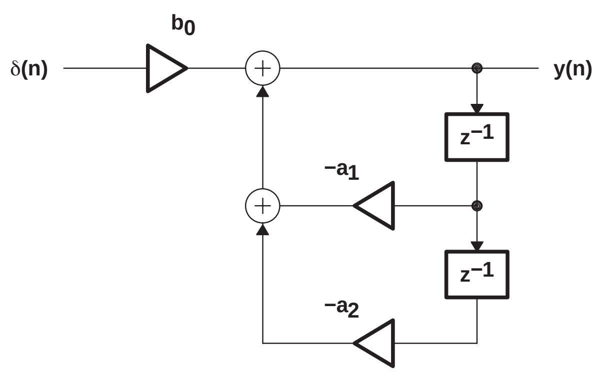

Figure 1. Difference Equation and Filter

$$y(n) = -a_1 y(n-1) - a_2 y(n-2) + b_0 \delta(n) \tag{1}$$

where

$$y(-1) = y(-2) = 0,\ \ a_1 = -2\cos(\omega_0),\ \ a_2 = 1,\ \ b_0 = A\sin(\omega_0),\ \ w_0 = \frac{2\pi f_0}{f_s}\ .$$

f_S is the sampling frequency, f_0 is the desired oscillating frequency, and A is the amplitude of the sinusoidal wave.

The advantage of this digital oscillator is that it does not consume much memory space and MIPS. However, it may cause instability because positive feedback is employed.

Another approach of generating a sine wave is based on a look-up table. Starting with an analog sine wave expression and taking its samples at a fixed regular interval at the rate n:

$$x(t) = \sin(2\pi Ft + \theta), \quad \theta \text{ is the initial phase angle} \tag{2}$$

$$x(n) = \sin(2\pi fn + \theta), \quad \text{where } n = 0, 1, 2, \ldots, f = F/F_s \tag{3}$$

F is the analog frequency/desired frequency and F_S is the sampling frequency.

Hence, at every sampling interval, we will compute *x(n)* and pass it through the digital-to-analog converter to get the sine wave. Figure 2 illustrates this concept. By having different amplitudes being output at every sampling interval, a sine or cosine waveform of arbitrary frequency can be generated. The following paragraphs discuss how this can be achieved.

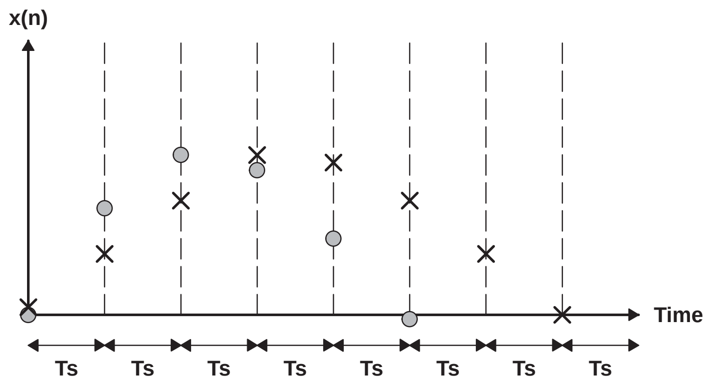

Figure 2. *x(n)* at Different Sampling Intervals

According to Equation (3), *x(n)* is computed based on the sine function, we now construct a table containing the values of the cosine function (see Appendix A). As it is not possible to construct all the values of the cosine and sine functions, the initial size is restricted to 517. Recognizing the fact that the cosine and sine functions are only phase-shifted by 90 degrees, the table size is reduced to 257. The table starts with 0 and ends with 180 degrees (π), and the interval between two entries in the table is 180/256 = 0.703125 degrees. Hence, the first entry in the table is the value of cos(0), the second entry is the value of cos(0.703125), the third is the value of cos(1.4063), and so on, until the value of cos(180) is reached. The phase step of the constructed waveform is always in a multiple of 0.703125 degrees.

The sinusoid waveform synthesis can be understood by considering the following waveforms again:

$$x(t) = \sin(2\pi Ft + \theta)$$

$$x(n) = \sin(2\pi fn + \theta), \quad \text{where } n = 0, 1, 2, \ldots, f = F/F_s$$

F is the analog frequency and F_S is the sampling frequency.

The value of n increases at every sampling interval. The sampled version of the analog signal is constructed as n increases. The following paragraphs explain how to read the value of sin($2\pi fn$) from the cosine table. As the table already contains values of the cosine function in increments of 0.703125 degrees, the question now is how to estimate the value of $2\pi fn$ as n increases.

The basic idea is to keep track of the starting and present phases of the waveform so that a continuous-phase sine wave can be obtained. By knowing or remembering the previous phase that has been output, the next amplitude to be output is then calculated. The next phase (that corresponds to the next amplitude) is incremented according to the desired output frequency. With this calculated new phase, the amplitude can be read off the look-up table and output to the CODEC.

Assume that the starting phase of the output signal to be stored in data memory is ***Init_Phase***. The phase step of the desired frequency is stored in ***Phase_Step***. The magnitude of the phase step is calculated using Equation (4).

$$\text{Phase\_Step} = \frac{\text{Desired frequency}}{\text{Sampling frequency}} \times 2\pi = 2\pi f \tag{4}$$

Therefore, if the desired frequency is 10 kHz with a sampling frequency of 44.1 kHz, the phase step is:

$$\text{Phase\_Step} = \frac{10000}{44100} \times 2\pi = 0.4535\pi \text{ (radians)} = 81.6 \text{ (deg)}rees.$$

The amplitude to be output at every sample interval is $\sin(0.4535\pi n)$, where n = 0, 1, 2,…. Therefore, the phase of the next output sample is:

Present Phase to be output = Previous phase + Phase Step

If the starting phase of the signal is 0 degree, then the next phase is 81.6 degrees, 163.2 degrees, and so on. These phase angles are used for calculating which amplitude to read from the cosine look-up table. For ease of representation of the phase in Q15 format, the calculated present phase is normalized by π. Table 1 shows some common phase values and their corresponding fixed-point Q15 representation in hexadecimal format.

Table 1. Hexadecimal Value for Some Common Phases

Phase (Radians)	Normalized by π	Q15 Number (Hex)
π/4	1/4	2000
π/2	1/2	4000
3π/4	3/4	6000
–π	−1	8000
–3π/4	−3/4	A000

Since the look-up table is based on cosine values, the normalized phase has to be further subtracted by π/2 (4000h) in order to generate the sine wave. However, if the cosine wave is desired, this subtraction is not necessary. Next, this phase value is used to read the correct amplitude from the look-up table. The values of cos(0), cos(π/2), and cos(π) are mapped to the memory addresses of the look-up table COSOFF, (COSOFF + 128), and (COSOFF + 256), respectively. For example, if the starting phase of the signal is –119.53 degrees, then the location in the cosine table is calculated as follows:

Location in cosine table = −119.53/(0.703125) = −170

Therefore, the corresponding cosine value can be read from (COSFF+170) because the value of cos(−119.53) is equal to that of cos(119.53). This is why the cosine table is used instead of the sine table. Hence, the starting phase, when normalized to the size of the look-up table, is:

Init_Phase = (−170/256) = A600h (Q15 format)

The normalized starting phase ranges from −1 to 1, which correspond to –180 degrees and 180 degrees, respectively.

If the desired output frequency is 10 kHz, then the phase step (in Q15 format), $2\pi f$, with a sampling frequency of 44.1 kHz is:

$$\textbf{\textit{Phase\_Step}} = 2 \times (10/44.1) * 32768 = \text{3A0Ch (normalized by } \pi)$$

Assuming that the amplitude corresponding to the starting phase has been output. The next phase angle, $2\pi fn$, for $n = 1$, is calculated as follows:

Present output phase (***Current_Phase***)	=	***Init_Phase*** + ***Phase_Step***	
	=	A600h + 3A0Ch	
	=	E00Ch	
Init_Phase	=	***Current_phase***	; For continuous phase

This value needs to be subtracted by π/2 (4000h) to obtain the sine value:

Sine_Phase	=	E00Ch − 4000h
	=	A00Ch

A negative value implies that a negative offset from the cosine table is needed to obtain this sine value. As explained previously, reading the value from the cosine table using the absolute value gives the same result. The absolute value of the phase angle is computed as follows:

Absolute Phase Angle = ABS[Sine_Phase] = ABS[A00Ch] = 5FF4h

The offset from the cosine table address is thus generated from the above calculation. By adding this offset to the start of the COSINE table, the next amplitude sample can be obtained. Using the above absolute phase angle, the offset is 5FF4h/80h = BFh = 191 (decimal). The amplitude at location 158 of the cosine look-up table is the next output.

COSOFF + (5FF4h/80h) = COSOFF + BFh

The value at look-up table is:

Cos(191/256)*π) = − 0.698

This value is passed to the DSP CODEC for output. The amplitude to be output is rounded off to the nearest integer so that the pointer can point to a memory location in the look-up table. The advantage is that continuous phase signal is maintained.

References

1. Dimitris G. Manolakis and John G. Proakis, *Digital Signal Processing: Principles, Algorithms, and Applications*, 3rd ed., Prentice Hall, New Jersey, 1996.
2. *DTMF Tone Generation and Detection: An Implementation Using the TMS320C54x* application report (SPRA096)
3. *Implementation of an FSK Modem Using the TMS320C17* application report (SPRA080)

Appendix A Cosine Table

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*   Copyright (C) 2001, Texas Instruments, Inc.  All rights reserved.
*   Francis Kua, Jun , 2001
*
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.word 0a416h   ; Cos 147.656250 (Degree) = –0.844854
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.word 09d16h   ; Cos 155.390625 (Degree) = –0.909168
.word 09c8ah   ; Cos 156.093750 (Degree) = –0.914210
.word 09c01h   ; Cos 156.796875 (Degree) = –0.919114
.word 09b7dh   ; Cos 157.500000 (Degree) = –0.923880
.word 09afch   ; Cos 158.203125 (Degree) = –0.928506
.word 09a7fh   ; Cos 158.906250 (Degree) = –0.932993
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.word 09626h   ; Cos 166.640625 (Degree) = –0.972940
.word 095d9h   ; Cos 167.343750 (Degree) = –0.975702
.word 09590h   ; Cos 168.046875 (Degree) = –0.978317
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.word 09335h   ; Cos 180.000000 (Degree) = –1.000000
```

Appendix B Software Listing

```
*************************************************
*           SineWave Generator
*************************************************
*********************************************************
*  freq  = 2*Desired F/Fs *(32768)
*  F     = Desired Frequency
*  Fs    = Sampling Frequency = 44100hz in this case
*******************************************************
FREQ1000    .set  1486
FREQ1750    .set  2600
FREQ2000    .set  2972
FREQ3000    .set  4458
FRAME_SIZE  .set 64
            .mmregs
            .include "cos256_tbl.inc"
            .global COSINE_BUFFER
            .global FREQ_BUFFER
            .bss  TEMP,1
            .bss  FREQ_BUFFER,128
            .bss  COSINE_BUFFER,257
            .bss  _FREQ_STEP,1
            .bss  _INIT_PHASE,1
            .def  FREQ
STK         .usect  "STACK",100
            .mmregs
            .sect   "CODE"
FREQ:       SSBX     OVM
            SSBX     SXM
            SSBX     FRCT
            NOP
            NOP

            STM      #STK+100H,SP
            STM      #001EH,PMST


            ST    #FREQ1000,*(_FREQ_STEP)     ;
            ST    #0,*(_INIT_PHASE)           ;
            STM   #FREQ_BUFFER,AR3            ;
```

```
            CALL     COPY_COS_TBL              ;
            CALL     GEN_FREQ                  ;
LOOP:       B        LOOP                      ;
;**********************************************
;         SINEWAVE GENERATOR ROUTINE
;**********************************************
GEN_FREQ:   STM       #FRAME_SIZE-1,BRC        ;
            RPTB      sine1-1

            LD       *(_FREQ_STEP),A           ;
            ADD      *(_INIT_PHASE),A          ;A=PRESENT PHASE
            STL      A,*(_INIT_PHASE)          ;SAVE PRESENT PHASE

            SUB      #4000H,A                  ;SUB PI/2 FOR SINE
            ABS      A                         ;Acc CONTAINS THE OFFSET
            STL      A,*(TEMP)                 ;
                                               ;
            LD       *(TEMP),9,A               ;
            STH      A,*(TEMP)                 ;
            LD       *(TEMP),A                 ;
            ABS      A                         ;
            ADD      #COSINE_BUFFER,A          ;
            STLM     A,AR2                     ;
            nop                                ;
            nop                                ;
            LD       *AR2,A                    ;
            STL      A,*AR3+                   ;
                                               ;
sine1:      NOP                                ;
            RET                                ;

COPY_COS_TBL:
            STM      #COSINE_BUFFER,AR2
            RPT      #257-1
            MVPD     #COSOFF,*AR2+
            RET
```

IMPORTANT NOTICE

Following are URLs where you can obtain information on other Texas Instruments products and application solutions:

Products		**Applications**	
Amplifiers	amplifier.ti.com	Audio	www.ti.com/audio
Data Converters	dataconverter.ti.com	Automotive	www.ti.com/automotive
DSP	dsp.ti.com	Broadband	www.ti.com/broadband
Interface	interface.ti.com	Digital Control	www.ti.com/digitalcontrol
Logic	logic.ti.com	Military	www.ti.com/military
Power Mgmt	power.ti.com	Optical Networking	www.ti.com/opticalnetwork
Microcontrollers	microcontroller.ti.com	Security	www.ti.com/security
		Telephony	www.ti.com/telephony
		Video & Imaging	www.ti.com/video
		Wireless	www.ti.com/wireless

Mailing Address: Texas Instruments
Post Office Box 655303 Dallas, Texas 75265