ANALOG DEVICES

AN-319
APPLICATION NOTE

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# Simple Interface Between D/A Converter and Microcomputer Leads to Programmable Sine-Wave Oscillator

by John Wynne

This application note outlines a very simple interface between the AD7542, a 12-bit CMOS D/A converter, and one of the most popular industry building blocks available, the 8-bit MCS-48 microcomputer family. The interface is used in a circuit which generates programmable low distortion sine waves. The circuit is based upon repeatedly adding a known constant to an accumulator which in turn scans a sine look-up table. The data from this table is presented to the DAC for conversion into an analog waveform. Changing the constant changes the generated output frequency.

## THE INTERFACE

The AD7542 accepts data in three 4-bit nibbles over a 4-bit wide data bus. The data is stored in three 4-bit data registers until, under program control, the new 12-bit word is transferred to the DAC register to update the analog outputs (see Figure 1). Internal register selection is achieved by decoding the address inputs A0 and A1 as shown in Table I. All data loading or data transfer operations are synchronized to the rising edge of the control signal $\overline{WR}$.

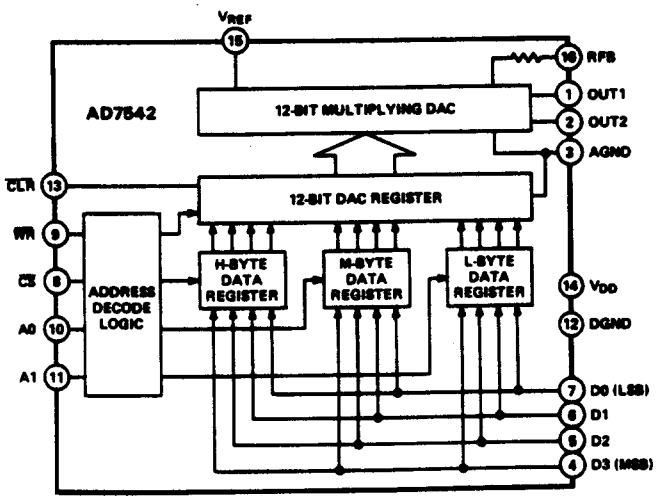


*Figure 1. AD7542 Functional Block Diagram*

| A1 (Pin 11) | A0 (Pin 10) | Register Selected |
|---|---|---|
| 0 | 0 | Low Byte Register |
| 0 | 1 | Mid Byte Register |
| 1 | 0 | High Byte Register |
| 1 | 1 | DAC Register |

*Table I. AD7542 Internal Register Decoding*

On all MCS-48 microcomputers the lower half of Port 2, P20–P23, can be used for I/O expansion with a dedicated I/O expander device, the 8243. The 8243 contains four 4-bit I/O ports which serve as extension of the on-chip I/O and are addressed as ports 4–7 with their own MOV, ANL and ORL instructions.

All communications between the MCS-48 microcomputer and the 8243 occurs over P20–P23 with timing provided by on output pulse on the PROG pin of the processor. The AD7542 is interfaced to the MCS-48 microcomputer over P20–P23 and is accessed by the processor as if it were an 8243. However, only the Transfer Accumulator to Port instructions are used in the interface. Each transfer consists of two 4-bit nibbles, the first containing the "op-code" and port address and the second containing the actual 4-bits of data.

Referring to Figure 2, a high to low transition of the PROG line indicates that address and op-code information are present on P20–P23. The port address on lines P20 and P21 must be externally latched at this point in time. The MCS-48 timing ensures that the falling edge of PROG coincides with the falling edge of ALE. Thus ALE is used to latch the port address information into an external 7475-type latch. The op-code information is not used in this application. When PROG returns high, the 4-bit wide bus contains valid data. By driving the $\overline{WR}$ input of the AD7542 with the PROG line, valid data is loaded into the AD7542 at this time.

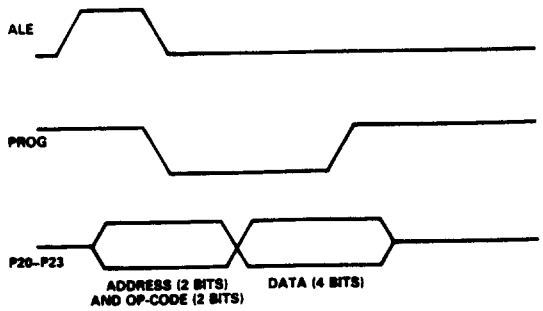


*Figure 2. Expander I/O Interface Timing*

| Nibble 1 | | | | Nibble 2 | | | |
|---|---|---|---|---|---|---|---|
| P23 | P22 | P21 | P20 | P23 | P22 | P21 | P20 |
| X | X | A | A | D | D | D | D |
| Op-Code Address | | | | (MSB) DATA (LSB) | | | |

| A (P21) | A (P20) | Port Selected |
|---|---|---|
| 0 | 0 | Port 4 |
| 0 | 1 | Port 5 |
| 1 | 0 | Port 6 |
| 1 | 1 | Port 7 |

*Table II. Expander I/O Multiplexed Bus (P20-P23)*

Table II shows the two nibbles of a transfer instruction. Comparing Table II with Table I, it can be seen that the address of the Low Byte register is the same as the Port 4 address in the I/O expansion mode. Thus a TRANSFER ACCUMULATOR TO PORT 4 instruction will in fact load the Low Byte register of the AD7542. A similar correspondence exists between the remaining AD7542 registers and the MCS-48 expansion ports. Only four instructions are thus required to load the AD7542:

```
MOVD  P4, A   Load Low Byte register
MOVD  P5, A   Load Mid Byte register
MOVD  P6, A   Load High Byte register
MOVD  P7, A   Load DAC register
```

The basic hookup is shown in Figure 3.

The advantage of this interface lies in its simplicity. In either single or multi-DAC applications, mapping the AD7542's as I/O devices greatly simplifies both the software and the chip select decoding over what would be required if the devices were memory mapped (in external data memory).

Multiple AD7542s can be connected to P20–P23 if additional chip select lines are supplied for the additional devices. For instance using the top half of Port 2 (P24–P27) directly as chip selects allows a maximum of four AD7542s on the I/O port; using P24–P27 with a 4-to-16 line decoder (such as the 8205) allows a maximum of sixteen AD7542s on the port.

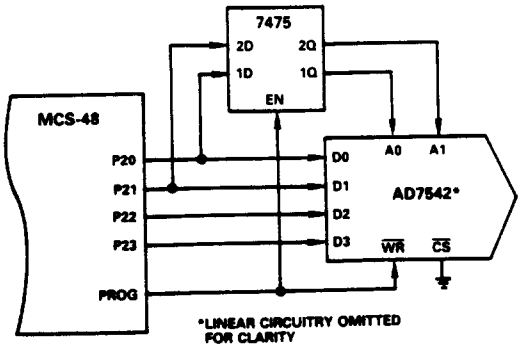


*Figure 3. Basic AD7542 to MCS-48 Interface*

## PROGRAMMABLE SINE-WAVE GENERATOR

One method of generating sine waves is to drive an up-counter at a given clock rate, the output of the counter being applied to a look-up table containing phase-angle information. This data in turn is fed to a DAC which generates the sampled waveform. A low-pass filter is then used to smooth the output waveform. The easiest way to change the output frequency is to increase the rate at which the counter is driven. However, changing the fundamental sampling frequency has severe implications for the output filter. If the software that loads the counter, instead of incrementing it by one per loop, increases the counter by two in the same period of time, the counter fills and rolls over twice as quickly. Thus, although the rate of counter loading–the sampling frequency–remains the same, doubling the loaded value–the frequency constant–doubles the output frequency. In the same way, each integer multiple of the initial frequency constant produces a corresponding multiplication of the output frequency. This is the basis of the technique used here and is described in more detail in References 1–3. The references also include software examples for using the circuit to generate touch-tone frequencies for telecommunication applications.

The number of bits in the accumulator (or counter), m, is determined by the resolution required in output frequency variation. The number of possible output signal frequencies is $2^{m-1}$, and the spacing between them is inversely proportional to $2^m$. A 14-bit accumulator is sufficient for the 1Hz spacing required here. The generated output frequency is given by

$$f_s = \frac{N.fc}{2^m}$$

where: N is the frequency constant which establishes the output frequency.

$f_c$ is the frequency of executing the loop, i.e., the sampling frequency.

m is the number of bits in the accumulator

Choosing a base frequency constant of 1 to produce a 1Hz output signal ensures that all other frequency constants N always equal the output frequency. Thus for a 14-bit counter to increment in single steps and roll over to zero once per second, requires a sampling rate of $2^{14}$ samples/sec (a sampling frequency of 16,384Hz). Thus each timing

loop should take 61.035μs to execute. For the MCS-48 family, the external crystal frequency is divided by fifteen to provide the internal machine cycle time. A crystal of 4.9155MHz gives a machine cycle time of 3.056μs which means 20 machine cycles per timing loop. Any branch in the program must be tailored so that a complete loop through the program will always take 20 machine cycles.

**THE SINE TABLE**

The MCS-48 architecture limits the external look-up table to 256 entries. Thus, 256 bytes encode the sine functions 360° in 1.406° steps (360/256). Placing the full 360° in the look-up table simplifies the software at the expense of increased distortion in the output. The synthesis program of Reference 2 stores a quarter period (first quadrant) of the output waveform in the look-up table and gives the software required to generate the additional quadrants.

The high byte of the 14-bit accumulator is used as a pointer to reference the look-up table. The complete look-up table is shown in Table III along with the BASIC program used to generate the table on an AIM-65. The AD7542 in Figure 5 is arranged for bipolar operation with offset binary coding. To ensure that the output waveform is symmetrical around 0V, the entries in the look-up table are adjusted so that the value FFH is assigned to the greatest positive amplitude equal to ($V_{REF}$ – 1LSB) for 90°, and the value 01H to the greatest negative amplitude equal to–($V_{REF}$ – 1LSB) for 270°. This allows the output for 0° and 180° to fall exactly on 80H–equivalent to 0V output for bipolar operation.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 0700 | 80 | 83 | 86 | 89 | 0780 | 80 | 7D | 7A | 77 |
| 0704 | 8C | 90 | 93 | 96 | 0784 | 74 | 70 | 6D | 6A |
| 0708 | 99 | 9C | 9F | A2 | 0788 | 67 | 64 | 61 | 5E |
| 070C | A5 | A8 | AB | AE | 078C | 5B | 58 | 55 | 52 |
| 0710 | B1 | B3 | B6 | B9 | 0790 | 4F | 4D | 4A | 47 |
| 0714 | BC | BF | C1 | C4 | 0794 | 44 | 41 | 3F | 3C |
| 0718 | C7 | C9 | CC | CE | 0798 | 39 | 37 | 34 | 32 |
| 071C | D1 | D3 | D5 | D8 | 079C | 2F | 2D | 2B | 28 |
| 0720 | DA | DC | DE | E0 | 07A0 | 26 | 24 | 22 | 20 |
| 0724 | E2 | E4 | E6 | E8 | 07A4 | 1E | 1C | 1A | 18 |
| 0728 | EA | EB | ED | EF | 07A8 | 16 | 15 | 13 | 11 |
| 072C | F0 | F1 | F3 | F4 | 07AC | 10 | 0F | 0D | 0C |
| 0730 | F5 | F6 | F8 | F9 | 07B0 | 0B | 0A | 08 | 07 |
| 0734 | FA | FA | FB | FC | 07B4 | 06 | 06 | 05 | 04 |
| 0738 | FD | FD | FE | FE | 07B8 | 03 | 03 | 02 | 02 |
| 073C | FE | FF | FF | FF | 07BC | 02 | 01 | 01 | 01 |
| 0740 | FF | FF | FF | FF | 07C0 | 01 | 01 | 01 | 01 |
| 0744 | FE | FE | FE | FD | 07C4 | 02 | 02 | 02 | 03 |
| 0748 | FD | FC | FB | FA | 07C8 | 03 | 04 | 05 | 06 |
| 074C | FA | F9 | F8 | F6 | 07CC | 06 | 07 | 08 | 0A |
| 0750 | F5 | F4 | F3 | F1 | 07D0 | 0B | 0C | 0D | 0F |
| 0754 | F0 | EF | ED | EB | 07D4 | 10 | 11 | 13 | 15 |
| 0758 | EA | E8 | E6 | E4 | 07D8 | 16 | 18 | 1A | 1C |
| 075C | E2 | E0 | DE | DC | 07DC | 1E | 20 | 22 | 24 |
| 0760 | DA | D8 | D5 | D3 | 07E0 | 26 | 28 | 2B | 2D |
| 0764 | D1 | CE | CC | C9 | 07E4 | 2F | 32 | 34 | 37 |
| 0768 | C7 | C4 | C1 | BF | 07E8 | 39 | 3C | 3F | 41 |
| 076C | BC | B9 | B6 | B3 | 07EC | 44 | 47 | 4A | 4D |
| 0770 | B1 | AE | AB | A8 | 07F0 | 4F | 52 | 55 | 58 |
| 0774 | A5 | A2 | 9F | 9C | 07F4 | 5B | 5E | 61 | 64 |
| 0778 | 99 | 96 | 93 | 90 | 07F8 | 67 | 6A | 6D | 70 |
| 077C | 8C | 89 | 86 | 83 | 07FC | 74 | 77 | 7A | 7D |

*Table IIIa. Look-Up Table for 360° of Output Waveform*

```
L      = 3840
FOR X  = 0 to 255
LET A  = Sin [(X * 1.40625)/57.2958]
LET Y  = INT (128.5 + 127 * A)
POKE L, Y
LET L  = L + 1
NEXT X
END
```

*Table IIIb. Basic Program for AIM-65 Used to Generate Look-Up Table*

**SOFTWARE AND HARDWARE**

Figure 4 shows the arrangement of registers within the microcomputer. The accumulator is implemented with two 8-bit registers, Reg 0 and Reg 1. Register 0 is the least significant. The frequency constant N is stored in Reg 2 and Reg 3. Register 2 is the least significant. Both the 14-bit accumulator and the 14-bit wide frequency constant occupy the most significant 14-bits of their respective register pairs. The high byte of the 14-bit accumulator is used as the pointer for accessing the look-up table.

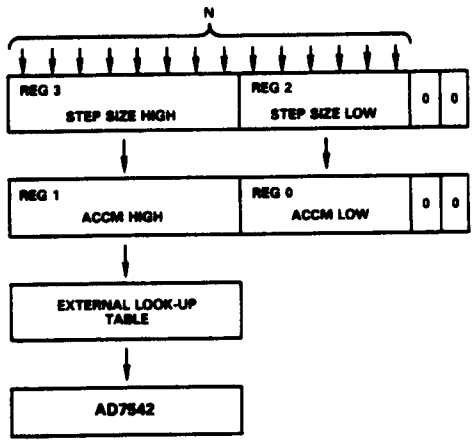


*Figure 4. Register Arrangement for Program*

The sequence of actions for the synthesis of a sine-wave output is shown in Table IV with the actual program listing in Table V. A circuit diagram of the synthesizer is shown in Figure 5. The 2716 EPROM contains both the program and the sine look-up table for the 8035. Program memory is all external and starts at location 000H, the address to which the processor is vectored after a Reset. The look-up table is treated as external data memory and occupies the highest page in the 2716–starting at 700H–for ease of decoding.

Bit 7 of Port 2 (P27) is used to differentiate between the high and low byte of the right-justified frequency constant N being loaded in through Port 1. A low level on P27 indicates the low byte (8LSB's) is present on P17–P10, a high level on P27 indicates the high byte (6LSB's) is present on P15–P10. For the program to work properly, the low byte of the frequency constant–with P27 low–must be present on Port 1 before a Reset is applied. Almost immediately after a Reset, the low byte is read and the program enters

a loop to allow the high byte of the frequency constant to be presented at Port 1. The program exits the loop–when P27 goes high–by reading the high byte. The frequency constant is next shifted left two places to position it properly in Registers 2 and 3 before the program enters the frequency synthesis loop properly.

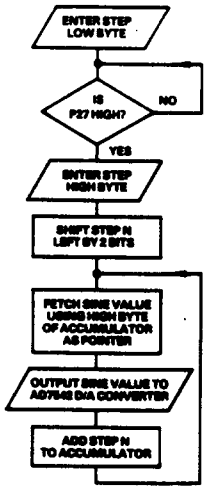


*Table IV. Sequence of Action for Sine-Wave Generation*

| | Location | Op-Code | Mnemonic | | Statement |
|---|---|---|---|---|---|
| | 0000 | 27 | CLR | A | |
| | 01 | A8 | MOV | R0,A | Clear 14-Bit Accumulator |
| | 02 | A9 | MOV | R1,A | |
| | 03 | 3C | MOVD | P4,A | Clear 4 LSB's of DAC |
| | 04 | 09 | IN | A,P1 | Get Low Byte of Frequency Constant |
| | 05 | AA | MOV | R2,A | |
| LOOP 1 | 06 | 0A | IN | A,P2 | Test for High Byte |
| | 07 | F7 | RLC | A | |
| | 08 | E6 | JNC | LOOP 1 | |
| | 09 | 06 | | | |
| | 0A | 09 | IN | A,P1 | Get High Byte of Frequency Constant |
| | 0B | AB | MOV | R3,A | |
| | 0C | 97 | CLR | C | |
| | 0D | FA | MOV | A,R2 | Shift Frequency Constant Two Places to the Left |
| | 0E | 6A | ADD | A,R2 | |
| | 0F | AA | MOV | R2,A | |
| | 10 | FB | MOV | A,R3 | |
| | 11 | 7B | ADDC | A,R3 | |
| | 12 | AB | MOV | R3,A | |
| | 13 | 97 | CLR | C | |
| | 14 | FA | MOV | A,R2 | |
| | 15 | 6A | ADD | A,R2 | |
| | 16 | AA | MOV | R2,A | |
| | 17 | FB | MOV | A,R3 | |
| | 18 | 7B | ADDC | A,R3 | |
| | 19 | AB | MOV | R3,A | |
| LOOP 2 | 1A | 81 | MOVX | A,R1 | Fetch Sine Value |
| | 1B | 3D | MOVD | P5,A | Output Sine Value to DAC |
| | 1C | 47 | SWAP | A | |
| | 1D | 3E | MOVD | P6,A | |
| | 1E | 3F | MOVD | P7,A | |
| | 1F | 97 | CLR C | | |
| | 20 | F8 | MOV | A,R0 | Update Low Byte of Accumulator |
| | 21 | 6A | ADD | A,R2 | |
| | 22 | A8 | MOV | R0,A | |
| | 23 | F9 | MOV | A,R1 | Update High Byte of Accumulator |
| | 24 | 7B | ADDC | A,R3 | |
| | 25 | A9 | MOV | R1,A | |
| | 26 | 00 | NOP | | Filler to Obtain Desired Sampling Frequency |
| | 27 | 00 | NOP | | |
| | 28 | 04 | JMP | LOOP 2 | |
| | 0029 | 1A | | | |

*Table V. Program Listing for Sine-Wave Generation*

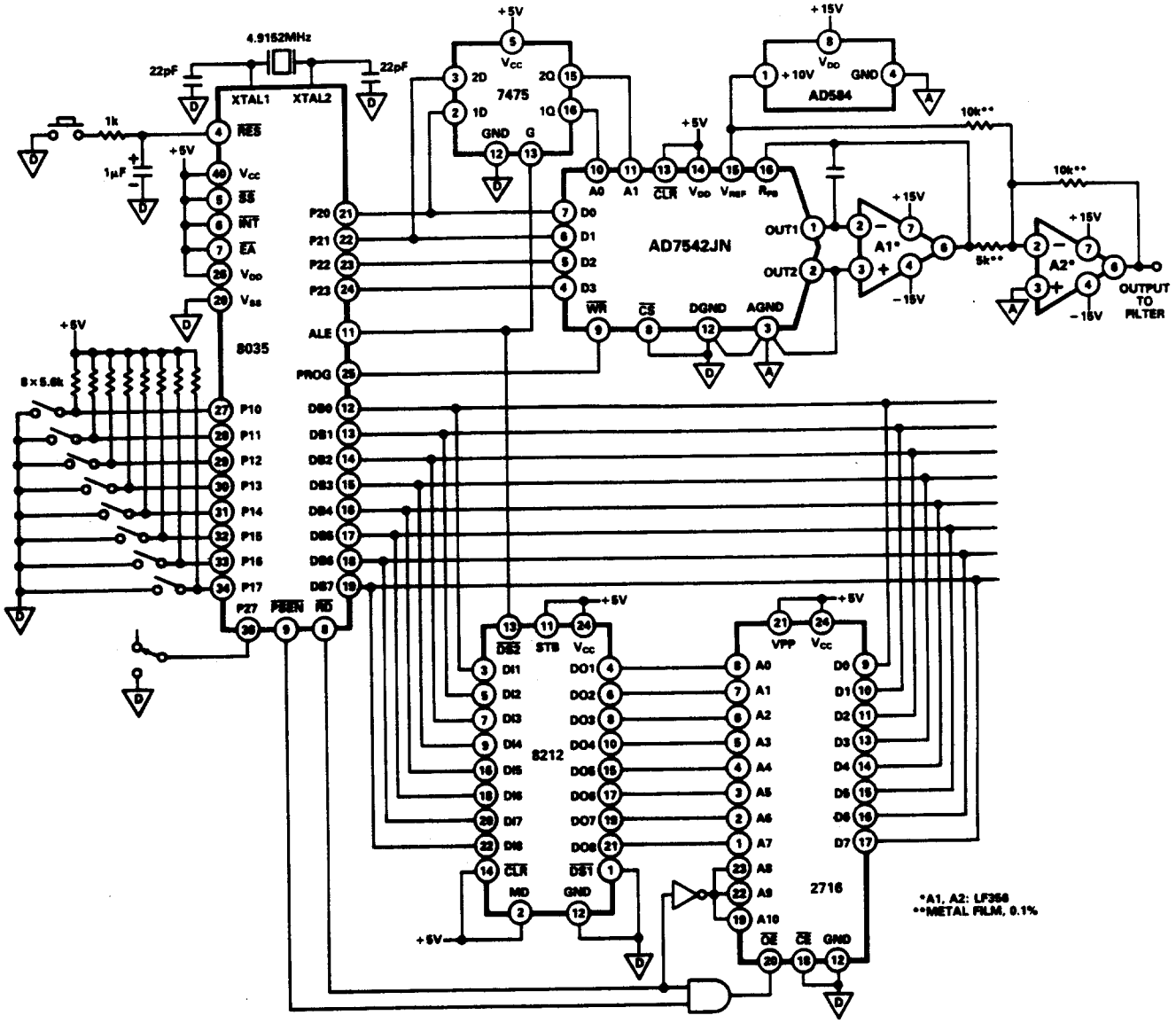


*Figure 5. Circuit Diagram of Frequency Synthesizer*

## EXPERIMENTAL RESULTS

The filter used to smooth the output waveform from the DAC is a sixth-order active RC low-pass filter (Reference 3) and is shown in Figure 6. The cut-off frequency is 4kHz. The response is down 58dB at 8kHz, half the sampling frequency. Experimental results are shown in Table VI.

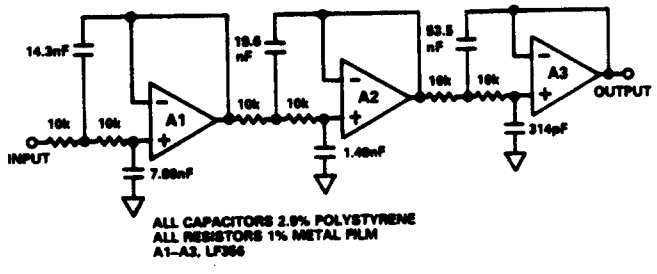


*Figure 6. Low-Pass Output Filter, 4kHz Bandwidth*

| Input Frequency Constant N in Decimal | Output Frequency | Total Harmonic Distortion (dB) |
|---|---|---|
| 0 | 0 | - |
| 1 | 1 | - |
| 16 | 16 | -48 |
| 17 | 17 | -48 |
| 32 | 32 | -52.6 |
| 33 | 33 | -48 |
| 64 | 64 | -54.8 |
| 65 | 65 | -43 |
| 128 | 128.01 | -56.2 |
| 129 | 129.01 | -44.7 |
| 256 | 256.02 | -54.6 |
| 257 | 257.02 | -45.2 |
| 512 | 512.05 | -55.4 |
| 513 | 513.05 | -44.1 |
| 1024 | 1024.1 | -55 |
| 1025 | 1025.1 | -45 |
| 2048 | 2048.2 | -52.4 |
| 2049 | 2049.2 | -44.8 |
| 4096 | 4096.4 | -57 |
| 4097 | 4097.4 | -47 |

*Table VI. Experimental Results from Frequency Synthesizer*

An interesting feature of the results in Table VI is the increased distortion of output waveforms whose frequencies are not integer power's of 2. For instance at $f_{OUT}$ = 1024Hz ($2^{10}$Hz) total harmonic distortion is −55dB; at $f_{OUT}$ = 1025Hz the output distortion is −45dB, an increase of 10dB. This is due to harmonics being generated at the "carry" frequency, the frequency at which the low byte of the 14-bit accumulator (in Reg 0) generates a carry to the high byte of the accumulator (in Reg 1). When synthesizing an output frequency of 1025Hz a carry between Reg 0 and Reg 1 is generated every 64 passes through the loop. Since one pass through the loop takes 61μs a series of harmonics spaced at 256Hz intervals is added to the output spectrum causing the 10dB deterioration in total harmonic distortion. See Figures 7a and 7b.

**ACKNOWLEDGMENTS**

To Norm Bernstein for originally suggesting the interface.

**REFERENCES**

1. J.E. Galbraith, "Generate Sine Waves by Direct Table Look-Up," EDN, April 28, 1982, pg 101.
2. T.S. Kinsel and J.H. Wuorinen, "A Digital Signal Generator," IEEE Micro, Nov, 1981, pg 6.
3. H. Chamberlin, "Musical Applications of Microprocessors," Hayden, 1980, pg 369.

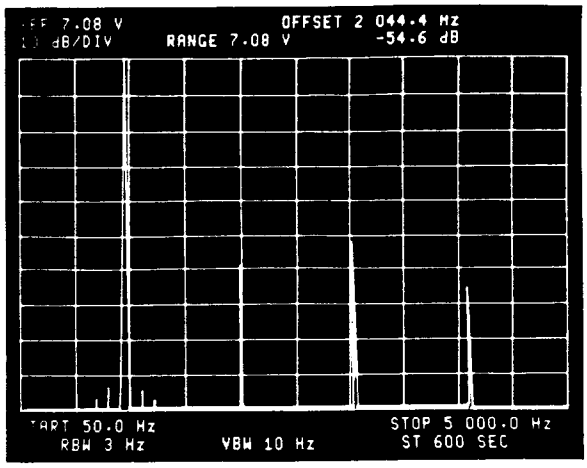


*Figure 7a. Output Waveform Spectrum for $F_{OUT}$ = 1024Hz*

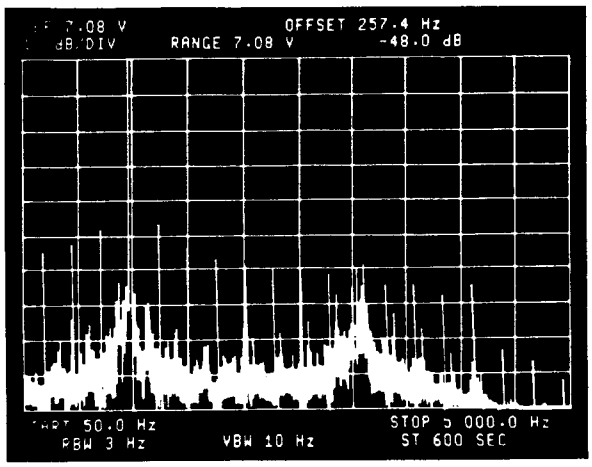


*Figure 7b. Output Waveform Spectrum for $F_{OUT}$ = 1025Hz*