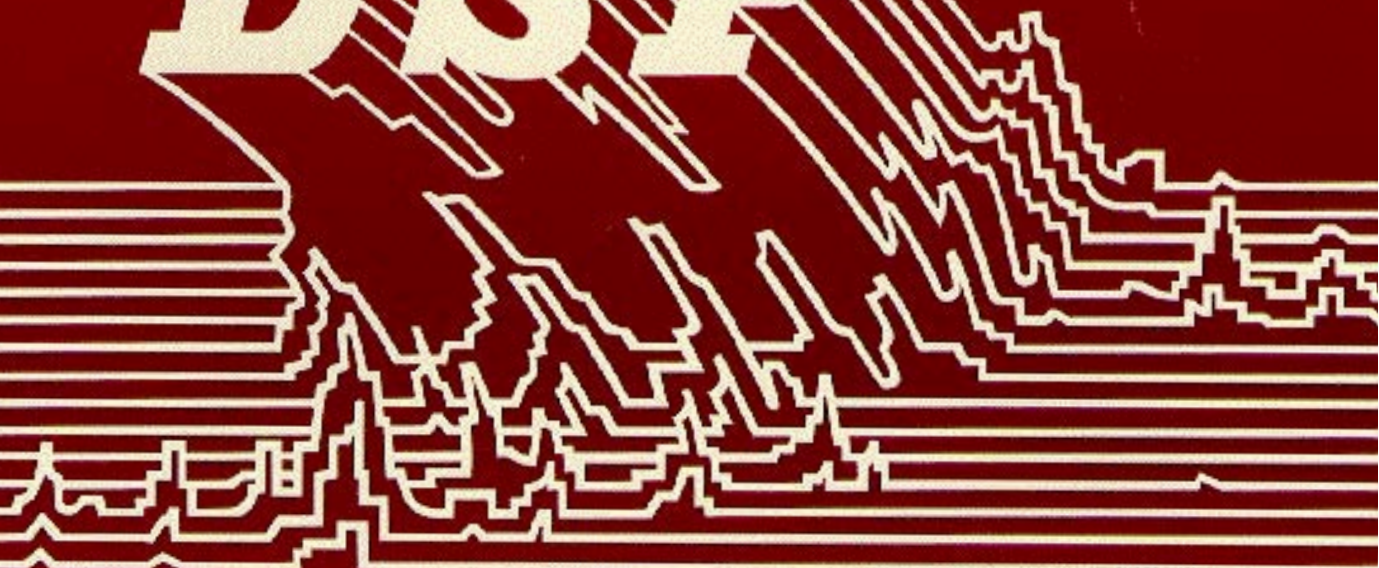


Digital Stereo 10-Band Graphic Equalizer Using the DSP56001

DSP



MOTOROLA

Digital Stereo 10-Band Graphic Equalizer Using The DSP56001

INTRODUCTION

A stereo 10-band graphic equalizer implemented with the DSP56001 is discussed in this application note. The theory behind the infinite impulse response (IIR) algorithm used to perform the bandpass filtering is examined briefly. The connection between the analog passive filter and the digital IIR filter is presented. Similar analytical techniques are employed to characterize the filter response in both the analog and digital domains. Exact algebraic expressions are derived relating center frequency (f_0), quality factor (Q), gain (G), and phase angle (ϕ) to the IIR coefficients. For frequencies much lower than one-half of the sample frequency, the gain and phase equations reduce to a simple form (symmetric over the logarithm of frequency), which is equivalent to those describing the resistor-capacitor-inductor (RCL) network of Figure 1(a). The IIR coefficients are easily obtained by evaluating these formulas based on a quality factor, center frequency, and center frequency (resonant frequency) gain (G_0). A graphic equalizer is composed of parallel filters with identical quality factor and center frequencies based on equal intervals of the log of frequency. Intervals differing by a factor of two (octaves) and ranging from 31 Hz to 16 kHz were chosen, thus covering most of the audio spectrum.

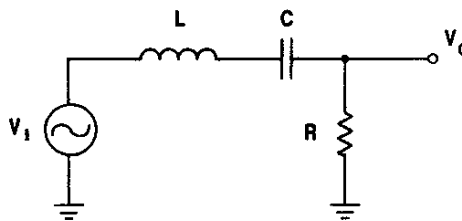


Figure 1(a). Analog Passive RCL Bandpass Network

The effect of coefficient quantization is shown to be severe for word size less than 24 bits. An approximate formula is derived to calculate the allowed quantized frequency bands as a function of the coefficient word length. The lowest allowed band for 16-bit coefficient word length is 54.8 Hz (using the transfer function of Equation (4)); whereas, it is 3.4 Hz for 24-bit coefficient word length. These results agree with those predicted by the "Filter Design & Analysis System" filter design software.¹

A hardware interface to a SONY 650ESD compact disk player utilizing the DSP56000/1's synchronous serial interface (SSI) port is described, thus yielding an all-digital graphic-equalizer system (i.e., analog-to-digital converter (ADC) and digital-to-analog converter (DAC) are not needed). This project demonstrates the use of the SSI port for receiving and transmitting data, the implementation of a set of parallel second-order IIR filters, and an example of a low-cost, memory-port bootstrap EPROM/DSP56001 system.

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FILTER ANALYSIS

The fundamental filter used is a bandpass, single-response pole, second-order IIR filter. (Even though two poles appear inside the unit circle in the z-plane, only one pole lies between 0 and π , the region of valid operation.) The filter center frequency, f_0 , and the bandwidth, Δf , can be adjusted through software control. The primary advantage of this second-order digital filter is the minimal number of instructions (a total of four adds and multiplies) needed to implement the algorithm.

THE PASSIVE SERIES RESONANT NETWORK

To describe the characteristics of the digital filter, the equivalent analog passive RCL bandpass network (Figure 1(a)) will be examined. By straightforward voltage divider analysis, the transfer function can be written as follows:²

$$\frac{V_o}{V_i} = \frac{R}{R + j(\Omega L - 1/\Omega C)} \quad (1a)$$

where $\Omega = 2\pi f$. The gain is the magnitude of Equation (1a):

$$G(\Omega) = \left[1 + Q^2 \left(\frac{\Omega^2 - \Omega_0^2}{\Omega \Omega_0} \right)^2 \right]^{-1/2} \quad (1b)$$

where $\Omega_0 = (LC)^{-1/2}$ and $Q = \Omega_0 L/R$. The phase angle, ϕ , is found by taking the ratio of the imaginary to real parts of the transfer function of Equation (1a):

$$\phi = \tan^{-1} \left[Q \left(\frac{\Omega_0^2 - \Omega^2}{\Omega \Omega_0} \right) \right] \quad (1c)$$

The equivalent s-plane expression is calculated by substituting $s = j\Omega$:

$$H(s) = \frac{Rs}{Rs + Ls^2 + 1/C} \quad (2)$$

An op-amp active-filter circuit with essentially the same response as the passive RCL network is shown in Figure 1(b).³ This active filter has several advantages over the passive network in that it eliminates the inductor; it is essentially isolated from input and output loading and can provide signal gain to the system.

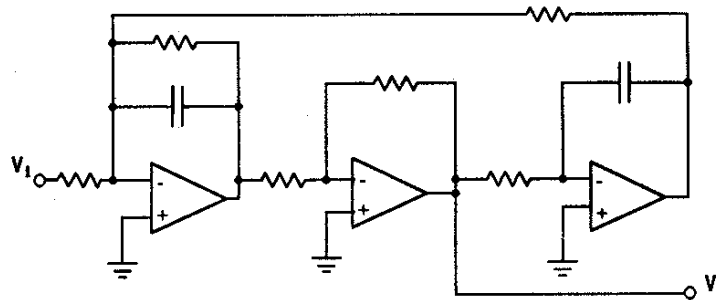


Figure 1(b). Op-Amp Active Bandpass Filter

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A digital-transfer-function representation of Equation (2) may be obtained by applying the bilinear transformation:^{4,5}

$$s = \frac{2}{T} \left(\frac{1-z^{-1}}{1+z^{-1}} \right) \quad (3a)$$

where $z=e^{j\theta}$, $\theta=\omega T$, and T is the sample period (see Figure 2). Equation (3a) can also be expressed as follows:

$$\Omega = \frac{2}{T} \tan(\theta/2) \quad (3b)$$

using the definitions of s and z . Substituting Equation (3a) into Equation (2) yields the z -plane transfer function:

$$H(z) = \frac{\alpha(1-z^{-2})}{1/2 - \gamma z^{-1} + \beta z^{-2}} \quad (4)$$

where the coefficients, α , β , and γ , are related to R , C , and L by

$$\alpha = \frac{RT/2}{T^2/2C + RT + 2L} \quad (5a)$$

$$\gamma = \frac{2L - T^2/2C}{T^2/2C + RT + 2L} \quad (5b)$$

$$\beta = \frac{T^2/4C - RT/2 + L}{T^2/2C + RT + 2L} \quad (5c)$$

The nonlinear relationship between the analog domain frequency, Ω , and the digital domain frequency, ω , as shown by Equation (3b), is often referred to as the frequency warp.⁶ As the frequency starts from zero, both Ω and ω are approximately equal, since the $\tan\theta \approx \theta$ for small angles. However, as Ω approaches infinity, ω approaches $2\pi f_s/2$. In this particular

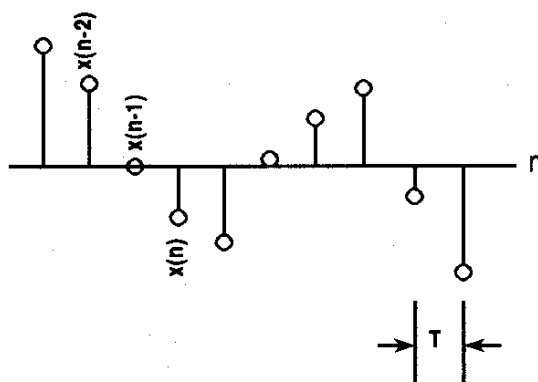


Figure 2. Standard Sampled Data, $x(n]$

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application, most of the interesting and useful frequencies satisfy the small angle approximation (SAA) where $\theta < \pi/4$. Thus, using the SAA simplifies the digital analysis, and a direct correspondance to the analog RCL network of Figure 1(a) is established. Although the SAA indeed simplifies the analysis, it must be used very carefully in derivations because the nature of this IIR filter depends on very small differences of numbers. If not used correctly, the SAA can mask out these differences and give totally erroneous results.

THE DIFFERENCE EQUATION

To implement the transfer function from Equation (4) as an IIR filter, it is first necessary to transform it to a difference equation in the discrete time domain. In this form, the filter can be directly implemented in software. Applying the inverse z-transform operator, Z^{-1} , to Equation (4), yields the following:⁷

$$Z^{-1}\{H(z)\} = Z^{-1}\{Y(z)/X(z)\} \quad (6a)$$

$$Z^{-1}\{Y(z)[\frac{1}{2} - \gamma z^{-1} + \beta z^{-2}]\} = Z^{-1}\{X(z)[\alpha(1 - z^{-2})]\} \quad (6b)$$

The time-delay property of the z-transform can be stated as follows:

$$X(z)z^{-m} = Z\{x(n-m)\} \quad (7)$$

where n is the discrete time index variable associated with continuous time sampling at a rate T (see Figure 2). Evaluating Equation (6b), using the property of Equation (7), gives the final IIR difference equation:

$$y(n) = 2\{\alpha[x(n) - x(n-2)] + \gamma y(n-1) - \beta y(n-2)\} \quad (8)$$

The coefficients, α , β , and γ , in the difference equation (Equation (8)) are used to adjust the filter response (gain and phase as a function of frequency). The representation of the time-varying data is based on standard notation used in digital filter theory.^{8,9,10} Thus, $x(n)$ is the current sampled data represented as an N-bit signed fraction; $x(n-1)$ is the previous data word; and $x(n-2)$ is the data word previous to $x(n-1)$. The n is the time index where it is assumed that the sample period, T , is constant and is related to the sample frequency, f_s , by $T = 1/f_s$. For example, the time between $x(n)$ and $x(n-2)$ is $2T$. Sampled values of the input signal are only collected at integral multiples of T (i.e., the $x(n)$'s are standard sampled/digitized data).

The $y(n)$ is similar to the input data, $x(n)$, but is instead the output data from the difference equation algorithm. As before, $y(n)$ is the current output value; $y(n-1)$ is the previous value; and $y(n-2)$ is the value previous to $y(n-1)$. Even though it is assumed that the input data is a signed fraction (a number between one and minus one), the $y(n)$'s can be greater than one (or less than minus one) unless scaling is performed to prevent this overflow condition. The choice of fractional values is not essential to proper behavior of the IIR algorithm, but it is a great convenience to both the analysis and the software implementation on the DSP56001.

The coefficients, α , β , and γ , in the difference equation (Equation (8)) are also fractional values (i.e., between one and minus one). As it will later be shown (Equation 15 with $G_0 = 1$), scaling at the output can be controlled by imposing the following condition on two of these three coefficients:

$$\alpha = \frac{1}{4} - \beta/2 \quad (9)$$

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This formula guarantees that, at the center frequency, the gain is one and the phase difference is zero. In this case, the bandpass filter acts as an attenuation filter (and phase shifter) for all frequencies other than the center frequency. Limiting the gain to one and the input to a fraction scaled to a maximum of one does not always prevent overflow at the output. For example, a square wave with an amplitude excursion from -1 to 1 has a fundamental sine component with an amplitude of $4/\pi$, which is greater than one by about 30 percent. Therefore, care must be exercised when specifying gain and dynamic range for filters to prevent distortion.

RESPONSE OF THE DIGITAL FILTER

The gain and phase response can be calculated solely from Equation (4). (The advantage of complex numbers is demonstrated in that both gain and phase information are present in the transfer function.) By definition, the gain is the absolute magnitude of $H(z)$. In the RCL circuit, the gain is simply the ratio of the resistance to the magnitude of the total complex impedance. The ratio of the real to imaginary components of impedance is equal to the tangent of the phase. Likewise, the ratio of real to imaginary components of $H(z)$ is equal to the tangent of the phase for the digital case.

Euler's identity is implemented to ease the calculation of gain, $G(\omega)$, and phase, $\theta(\omega)$:

$$e^{j\theta} = \cos\theta + j \sin\theta \quad (10)$$

The transfer function (Equation (4)) then becomes:

$$H(e^{j\theta}) = \frac{\alpha(e^{j2\theta} - 1)}{\frac{1}{2} e^{j2\theta} - \gamma e^{j\theta} + \beta} = \frac{\alpha(\cos 2\theta - 1) + j \sin 2\theta}{(\frac{1}{2} \cos 2\theta - \gamma \cos \theta + \beta) + j(\frac{1}{2} \sin 2\theta - \gamma \sin \theta)} \quad (11)$$

where $\theta = \omega T$. For example, $\theta = \pi/2$ would correspond to $f = f_s/4$ (since $\omega = 2\pi f$ and $T = 1/f_s$). If $f_s = 44.1$ kHz (the standard for compact disc digital audio), then $\theta = \pi/2$ would be a frequency of 11.025 kHz.

The filter gain is found by evaluating the following expression:

$$G(\omega) = [H(e^{j\theta})H^*(e^{j\theta})]^{1/2} \quad (12)$$

and, after some algebraic and trigonometric manipulations, becomes:

$$G(\omega) = \frac{2\alpha \sin \theta}{\{[(\frac{1}{2} - \beta)\sin \theta]^2 + [(\frac{1}{2} + \beta)(\cos \theta - \cos \theta_0)]^2\}^{1/2}} \quad (13)$$

where

$$\cos \theta_0 = \gamma / (\frac{1}{2} + \beta) \quad (14)$$

is the filter center frequency.

Examination of the gain in Equation (13) shows several important features:

- The gain, $G(\omega)$, is proportional to α .
- The gain at the center frequency, ω_0 , is

$$G_0 = 2\alpha / (\frac{1}{2} - \beta) \quad (15)$$

as previously noted in Equation (9).

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- The bandwidth is adjusted by β (that also effects the center frequency as shown by Equation (14)).
- Equation (13) is symmetric (neglecting the zero at $\theta = \pi$) on a logarithmic scale. This characteristic of the gain can be seen more easily by taking the SAA of Equation (13) where

$$\sin\theta \approx \theta \quad (16)$$

and

$$\cos\theta \approx 1 - \theta^2/2 \quad (17)$$

so that

$$G_a(\omega) = \frac{G_0}{\left[1 + \left(\frac{1/2 + \beta}{1/2 - \beta} \right)^2 \left(\frac{\theta_0^2 - \theta^2}{2\theta} \right)^2 \right]^{1/2}} \quad (18)$$

Substitution of $\theta = k\theta_0$ or $\theta = \theta_0/k$ yields equivalent values of gain, thus proving the gain is symmetric over the log of frequency. The subscript "a" denotes that the SAA was used in that expression.

The phase shift, $\phi(\omega)$, is found from the ratio of the imaginary to real part of $H(z)$ from Equation (11):

$$\tan \phi = \frac{\text{Im}[H(e^{j\theta})]}{\text{Re}[H(e^{j\theta})]} \quad (19)$$

After same algebraic and trigonometric manipulations, Equation (19) can be written as

$$\tan \phi = \frac{(1/2 + \beta)(\cos\theta - \cos\theta_0)}{(1/2 - \beta)\sin\theta} \quad (20)$$

Applying the SAA simplifies the previous result:

$$\tan \phi_a = \frac{(1/2 + \beta)(\theta_0^2 - \theta^2)}{(1/2 - \beta)2\theta} \quad (21)$$

The SAA can be used to approximate the filter center frequency, θ_0 , from Equation (14):

$$\theta_{0a} = \left[\frac{1 + 2\beta - 2\gamma}{1/2 + \beta} \right]^{1/2} \quad (22)$$

The SAA is accurate within a few percent for angles up to $\pi/4$. (This SAA corresponds to a filter frequency of $f < f_s/8$.)

The bandwidth of the filter is most easily determined from Equation (18). Generally, two frequencies are considered, one on each side of the center frequency, θ_0 . The gain at each of the frequencies, θ_1 and θ_2 , is equivalent and is commonly chosen so that the value of gain is $G_0/\sqrt{2}$. Since $20\log(1/\sqrt{2}) = -3$, the bandwidth can be defined as $\Delta\theta = \theta_2 - \theta_1$, where $G(\theta_1) = G(\theta_2) = G_0/\sqrt{2} = -3$ dB of the center frequency gain. As previously noted, $\theta_1 = \theta_0/k$ and $\theta_2 = k\theta_0$ for a filter symmetric about the center frequency over the log of frequency.

The Q of the filter in such a case is as follows:

$$Q = \frac{\theta_0}{\Delta\theta} = \frac{\theta_0}{k\theta_0 - \theta_0/k} = \frac{k}{k^2 - 1} \quad (23)$$

where $k > 1$. Since, by definition, the bandwidth is determined at the frequencies corresponding to a gain of $G_0/\sqrt{2}$, using Equation (18), the following term is equal to one:

$$\left(\frac{\frac{1}{2} + \beta_a}{\frac{1}{2} - \beta_a} \right)^2 \left(\frac{\theta_1^2 - \theta_0^2}{2\theta_1} \right)^2 = 1 \quad (24)$$

and using Equation (23) to solve for β_a in terms of Q yields

$$\frac{\frac{1}{2} + \beta_a}{\frac{1}{2} - \beta_a} = \frac{2}{\theta_0} \left(\frac{k}{k^2 - 1} \right) = 2Q/\theta_0 \quad (25)$$

Rearranging terms results in the final form:

$$\beta_a = \frac{Q - \theta_0/2}{2Q + \theta_0} \quad (26)$$

where $\theta_0 = 2\pi f_0/f_s$. The subscript "a" is used to denote that the SAA was used in this derivation (i.e., by definition of Q from Equation (18)).

Solving for γ in Equation (14) gives

$$\gamma = (\frac{1}{2} + \beta)\cos\theta_0 \quad (27)$$

For unity gain at the center frequency, α (Equation (15)) becomes

$$\alpha = (\frac{1}{2} - \beta)/2 \quad (28)$$

Equation (18) now simplifies to the following equation for gain:

$$G_a(\omega) = \left[1 + Q^2 \left(\frac{\theta_0^2 - \theta^2}{\theta_0\theta} \right)^2 \right]^{-1/2} \quad (29)$$

Equation (21) becomes

$$\phi_a(\omega) = \tan^{-1} \left[Q \left(\frac{\theta_0^2 - \theta^2}{\theta_0\theta} \right) \right] \quad (30)$$

Equations (13), (14), (15), and (20) provide a complete, theoretically accurate, concise description of the digital filter response described by the difference equation (Equation (8)). The coefficients, α and γ , can be found from β , θ_0 , and G_0 . β must be determined from the gain (Equation (13)) by picking $G(\theta_1)$ and θ_1 , then finding the value of β from the equality. These four equations are exact and can be used over the entire frequency range from 0 to π .

Equations (26) through (30) provide a simplified set of formulas that are reasonably accurate for $f < f_s/8$ and for unity gain at the center frequency.

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ANALYSIS CONSTRAINTS OF THE BILINEAR TRANSFORMATION

THE PASSIVE SERIES RESONANT NETWORK shows how to determine the IIR coefficients from the RCL values of a passive network filter based on the bilinear transformation. This technique is very powerful, especially if the frequencies of interest are much lower than the sample frequency (as is often true in digital audio applications) so that the SAA can be used. The resonant and cutoff frequency and quality factor, Q , of most RCL networks are known or can be easily determined. **THE DIFFERENCE EQUATION** discusses how to convert the transfer function to a difference equation, which is the final form (for software implementation) of the digital IIR filter. The relationship connecting the R , L , and C values of the analog filter to the coefficients α , β , and γ of the digital filter (from Equations 5a thru 5c) holds true only for frequencies where the SAA is valid. This frequency range makes up the linear region of the bilinear transformation where (from Equation 3b) $\tan \theta \approx \theta$. In this case, a direct correspondence between the response of almost any RCL network and an IIR filter's coefficients can be established, as previously demonstrated for the bandpass filter network. This technique lends itself to audio applications because the response of a network is usually described over the log of frequency. The audio range is basically logarithmic, thus the SAA applies to most of the range of interest since $f_s/8$ is very close to $f_s/2$ on a log scale (see Figures 11 and 12).

COEFFICIENT QUANTIZATION

Coefficient quantization is an effect that depends solely on the word length of the filter coefficients. Equations (13), (14), and (15) yield values for α , β , and γ for given values of center frequency and bandwidth. These formulas are exact. However, the word size of the variables used to represent the coefficients in the filter algorithm are of finite length. Therefore, only certain discrete values of center frequency, bandwidth, and resonant frequency gain are obtainable.

To analyze the effects of coefficient quantization in this particular digital filter, let N be the number of bits used to represent data in the algorithm. Assuming that the coefficients are fractions, the smallest number that can be represented is therefore (see reference 2):

$$\delta = 2^{-(N-1)} \quad (31)$$

Using Equation (31), β and γ can be represented as follows:

$$\gamma = 1 - n\delta \quad (32a)$$

$$\beta = \frac{1}{2} - m\delta \quad (32b)$$

since $\beta < \frac{1}{2}$ and $|\gamma| < 1$. This can be easily seen by evaluating the zeros of the transfer function (Equation 4) and then calculating the magnitude of that complex number. The resulting value is the distance from the origin to the pole in the complex plane and is equal to 2β . Now, since the poles must lie within the unit circle¹¹ $\beta < \frac{1}{2}$. Using Equation (14), it can be seen that $|\gamma| < 1$. The integers n and m take on values from 1 to 2^{N-1} . Equation (22) can be written as

$$\theta_0 = \left[\frac{1 + 2(\frac{1}{2} - m\delta) - 2(1 - n\delta)}{\frac{1}{2} + (\frac{1}{2} - m\delta)} \right]^{\frac{1}{2}} = \left[\frac{2(n - m)\delta}{1 - m\delta} \right]^{\frac{1}{2}} \quad (33)$$

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By inspection, the lowest nonzero value of θ_0 is with $n=2$ and $m=1$. The lowest obtainable frequency is then

$$f_0 = \theta_0 f_s / 2\pi = \frac{1}{2\pi} \left[2 \left(\frac{\delta}{1-\delta} \right) \right]^{1/2} = f_s 2^{-N/2/\pi} \quad (34)$$

Assuming $f_s=44.1$ kHz, the lowest obtainable frequency for 16 bits is 54.8 Hz; for 24 bits, it is 3.4 Hz. Clearly, 16 bits does not yield the coefficient accuracy needed to implement filter responses in the low-frequency bands (i.e., 20 to 200 Hz) for audio applications. The 24-bit word length of the DSP56001 is more than enough to ignore coefficient-quantization errors.

HARDWARE DESCRIPTION

The basic hardware description of the SSI and compact disk player interface and a layout of the system are presented in the following paragraphs.

SSI AND COMPACT DISK PLAYER INTERFACE

Figure 3(a) shows the data signals tapped from the compact disk player (CDP). Three of the four signals are clocks. The data line is cut to form two data signals, DATOUT and DATIN. The format of the data is stereo multiplexed (i.e., left-right-left-right. . .). The data length for each channel is 24 bits: 16 of which are significant; the upper eight are sign extended. Since the audio sample frequency used on the CDPs is 44.1 kHz, the bit clock (BITCLK) runs at 48×44.1 kHz = 2.1168 MHz. The word clock (WRDCLK) runs at 1/24 of the BITCLK, which is 88.2 kHz; the left-right clock (LRCLK) runs at 44.1 kHz. These signals are tapped from the CDP before the up-sampling section. The format of these signals varies among manufacturers and models; therefore, this particular application should only be used as an example.

The SSI consists of six pins, which are the upper bits of port C (PC3 through PC8):

PC3	SC0	Serial Control 0
PC4	SC1	Serial Control 1
PC5	SC2	Serial Control 2
PC6	SCK	SSI Serial Clock
PC7	SRD	SSI Receive Data
PC8	STD	SSI Transmit Data

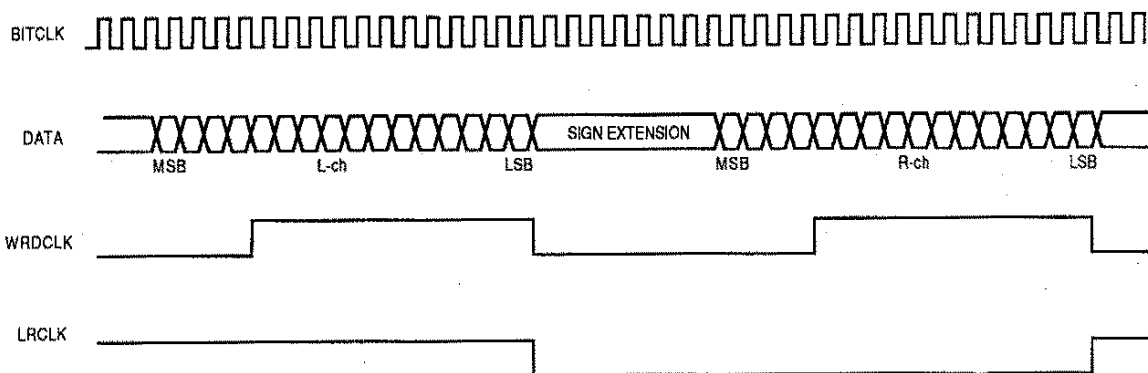


Figure 3(a). Signals Tapped from CDP

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Four memory-mapped hardware registers control the configuration and operation of the SSI port:

Port C Control Register	[X:\$FFE1]
Control Register A	[X:\$FFEC]
Control Register B	[X:\$FFED]
SSI Status Register	[X:\$FFEE]

The port C control register (PCC) is used to select port C pins as SSI or general-purpose input/output (I/O). If all of the SSI pins are to be used, bits 3 through 8 are set (i.e., PCC=\$1F8). The DPS56000/1 code for setting the PCC is as follows:

```
MOVEP    #$1F8,X:FFE1
```

where X:\$FFE1 is the memory address of the PCC register. In this particular example, shown in Figure 3(b), the CDP's WRDCLK is connected to SC2, which is configured as a frame sync. A frame then consists of one 24-bit word. The LRCLK is connected to SC0 as a serial input flag whose status can be determined by polling the SSI status register, bit 0 (IF0), shown in Figure 4.

The immediate value of #\$6000 is loaded into control register A for this particular implementation. This sets the word length to 24, ignores the clock prescaler (because an external clock is used), and selects the normal mode.

Control register B is loaded with #\$B200, which chooses synchronous mode, enables the receive and transmit shift registers, arms the receive interrupt, and sets the serial pins to inputs (SC0, SC1, SC2, and SCK). Note that the frame sync length is set to a word frame, which may at first appear to violate the SSI operation. However, since the frame sync is external, the actual sampling of the frame occurs during the first SSI clock cycle of the frame sync clock.

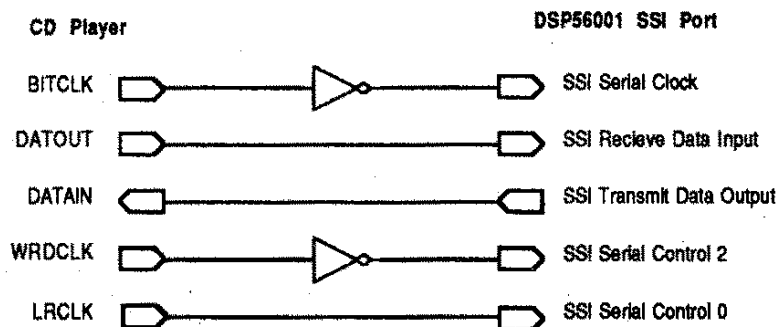


Figure 3(b). CDP to SSI Interface

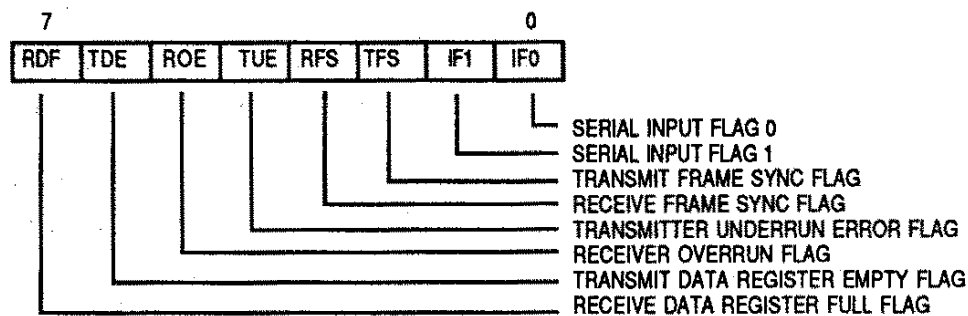


Figure 4. Read-Only SSI Status Register (X:\$FFEE)

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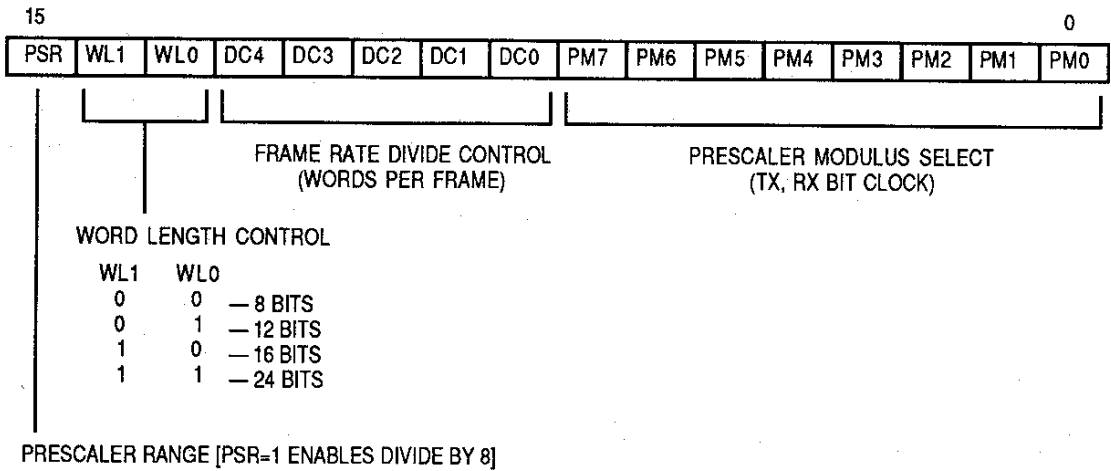


Figure 5. SSI Control Register A (X:\$FFEC)

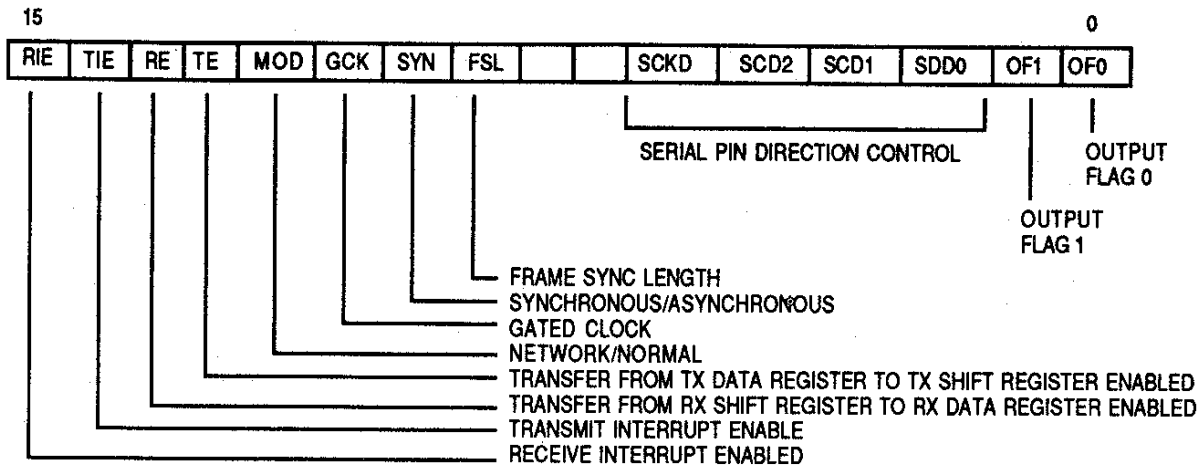


Figure 6. SSI Control Register B (X:\$FFED)

BLOCK DIAGRAM

The block diagram of Figure 7 shows the basic hardware layout of the system. The EPROM's data is loaded into the DSP56001 P:RAM upon powerup (or reset). Slide potentiometers, one for each frequency band, are multiplexed into an 8-bit ADC. The value of the voltage from each slide potentiometer is proportional to the gain used to multiply the particular bandpass filter response. Figure 8 is a complete schematic diagram of the system. The analog multiplexers used are three 4051, 8:1 MUXs. The address is generated by latching a 7-bit address with a 74LS374 octal D-type latch off the DSP56001's data bus. The ADC read enable is generated by ANDing the read (RD) and data strobe ($\overline{DS}$) from the DSP56001; the MUX select enable is generated by ANDing write (WR) and data strobe ($\overline{DS}$). With this particular system, only 20 slide potentiometers are used for setting frequency response; one is used for master volume. Therefore, a total of 21 channels of the MUX are used, resulting in only three of the four 4051s being used.

Data received at the SSI port initiates an interrupt every 11.3 ms (the inverse of 88.2 kHz). This is the rate at which 24 bits are read, corresponding to a complete word of data from the left or the right channels. SC0 (the LRCLK) is then polled to determine which channel

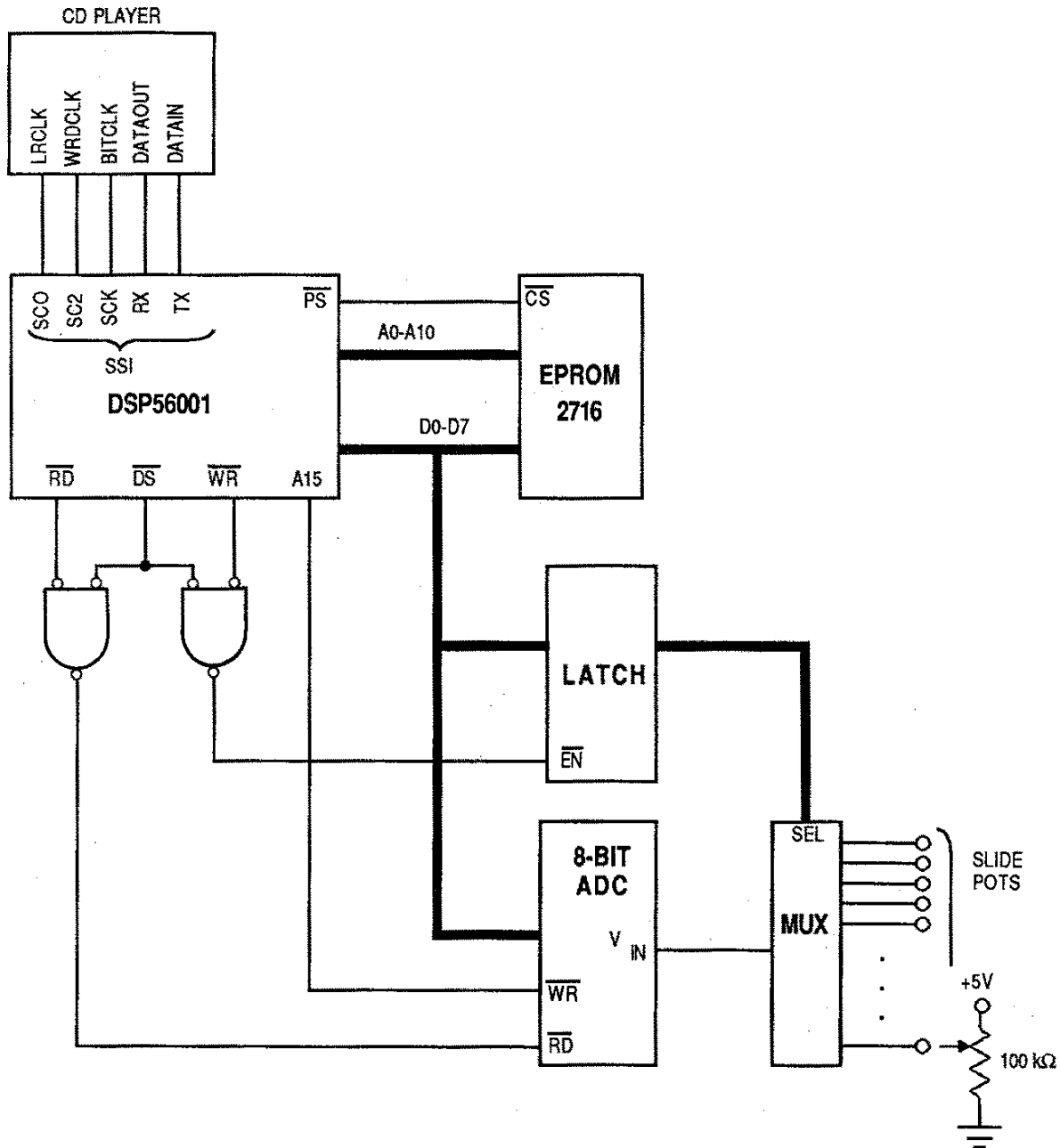


Figure 7. Block Diagram of DPS56001 Graphic Equalizer

needs processing. (In an optimized configuration, the LRCLK can also be used as the frame sync, using the network mode, where a frame consists of two 24-bit words, thus eliminating the need for the WRDCLK.) The received word is processed by the 10 parallel IIR filters, corresponding to the 10 left slide potentiometers or the 10 right slide potentiometers, and then transmitted back to the CDP. The CDP's DAC receives the data a total of two words later; thus, a latency of two sample periods has been introduced. This latency does not cause any undesirable effects since everything becomes delayed by the same amount. Jumpering the DATIN to DATAOUT will completely bypass the DSP56001 system and eliminate the delay (useful as the standard bypass mode of an audio equalizer). Equivalently,

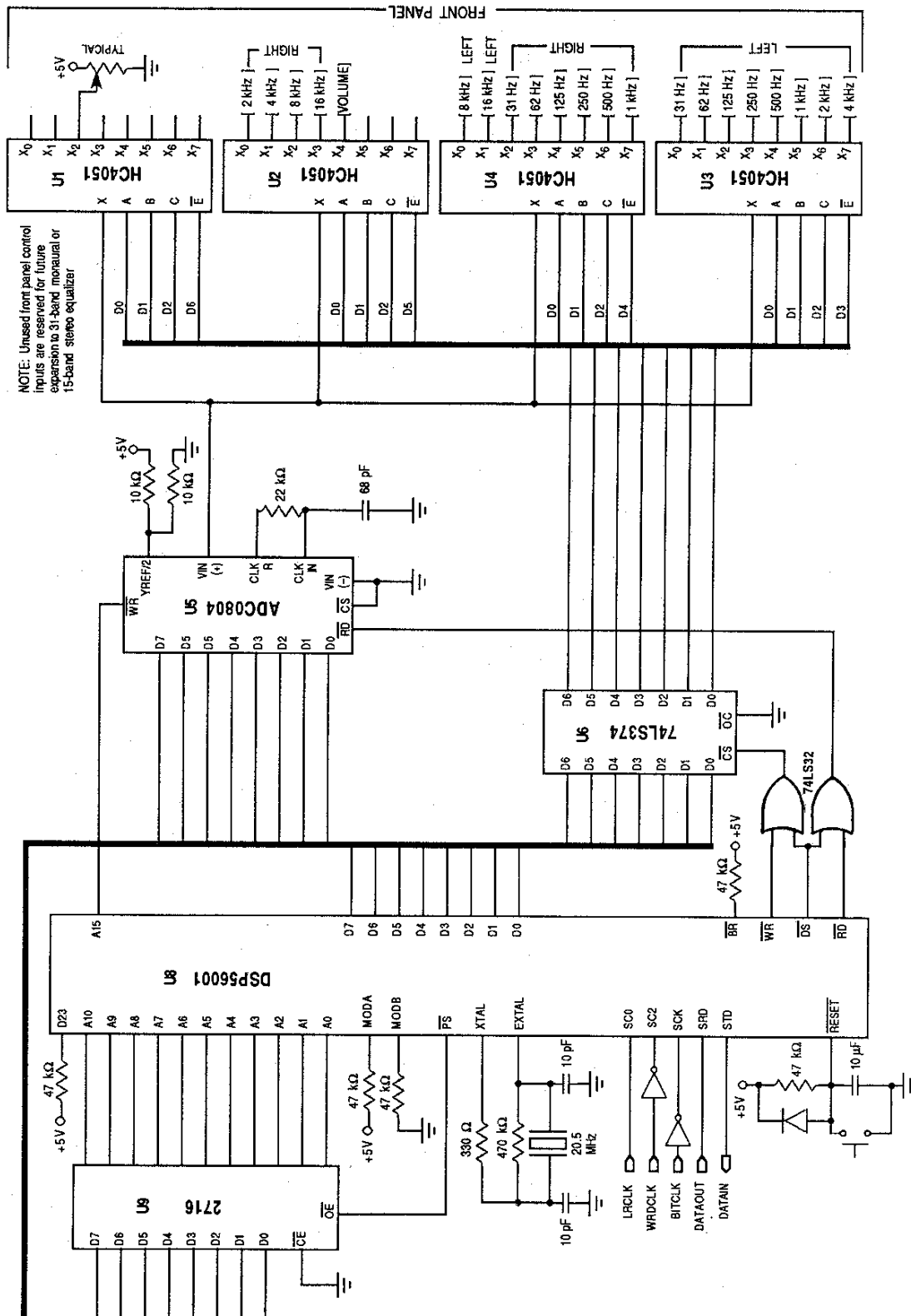


Figure 8. Schematic Diagram of DSP56001 Graphic Equalizer

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later; thus, a latency of two sample periods has been introduced. This latency does not cause any undesirable effects since everything becomes delayed by the same amount. Jumping the DATIN to DATOUT will completely bypass the DSP56001 system and eliminate the delay (useful as the standard bypass mode of an audio equalizer). Equivalently, the bypass mode can be achieved by receiving the data at the SSI and then transmitting the same data without processing (also a useful technique for debugging).

ALGORITHM AND SOFTWARE

The following paragraphs discuss the filter algorithm and the final implementation of the DSP56000/1 code.

FILTER ALGORITHM

Figure 9(a) shows a high-level implementation of the difference formula of Equation (8). The array indexes I, J, and K are modulo 3 (i.e., they will only contain the values 0, 1, and 2). The current value and previous two values of data are stored in a cyclic buffer (arrays X and Y). Figure 9(b) shows the input array, X, for the first four sample times. The output array, Y, is treated in a similar fashion.

```

I = 0
A = ALPHA      X(0) = 0      Y(0) = 0
B = BETA       X(1) = 0      Y(0) = 0
C = GAMMA      X(2) = 0      Y(2) = 0

100 READ ADC
X(I) = ADC
J = I-2        IF J < 0 THEN J = J+3
K = I-1        IF K < 0 THEN K = K+3
Y(I) = 2 * (A * (X(I) - X(J)) + C * Y(K) - B * Y(J))
OUTPUT Y(I) TO DAC
I = I + 1      IF I > 2 THEN I = 0
GOTO 100

```

**Figure 9(a). IIR Filter Algorithm (Equation (8))
Coded in a High-Level Language**

t = 1		t = 2	
I = 0	x(n) = ADC1	K = 0	x(n-1) = ADC1
J = 1	x(n-2) = 0	I = 1	x(n) = ADC2
K = 2	x(n-1) = 0	J = 2	x(n-2) = 0
t = 3		t = 4	
J = 0	x(n-2) = ADC1	I = 0	x(n) = ADC4
K = 1	x(n-1) = ADC2	J = 1	x(n-2) = ADC2
I = 2	x(n) = ADC3	K = 2	x(n-1) = ADC3

Figure 9(b). IIR Data Arrays During First Four Iterations

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The equivalent DSP56000 code to perform the IIR filter difference equation is shown as follows:

MOVE	X:ADC,B			;Read external ADC.
MOVE	B,Y:(R5)			;Store ADC value in
				; cyclic buffer as x(n).
CLR	B	X:(R0)+,X0	Y:(R4)+,Y0	;Get β and $y(n-2)$.
MAC	-X0,Y0,B	X:(R0)+,X0	Y:(R5)+,Y0	;B = B - $\beta y(n-2)$.
MAC	X0,Y0,B		Y:(R5),Y0	;B = B + $\alpha x(n)$.
MAC	-X0,Y0,B	X:(R0)+,X0	Y:(R4)+,Y0	;B = B - $\alpha x(n-2)$.
MACR	X0,Y0,B			;B = B + $\gamma y(n-1)$.
MOVE	B,Y:(R4)-			;Store result in cyclic
				; buffer as y(n).
MOVE	B,X:DAC			;Write y(n) to external
				; DAC.

The code would often be an interrupt routine where the interrupt is activated by an external sample rate clock (such as a CDP). The first two instructions read the data from a memory-mapped ADC and store the data in the x(n) array. The next five instructions perform the four multiply/accumulates necessary to implement the difference equation. The last two instructions store the result in y(n) and the memory-mapped DAC. The index registers, R0, R4, and R5, point to the coefficient table, y(n), and x(n), respectively (see Figure 10). Index registers, R0, R4, and R5, are modulo 3 as are the indexes I, J, and K in the high-level language example.

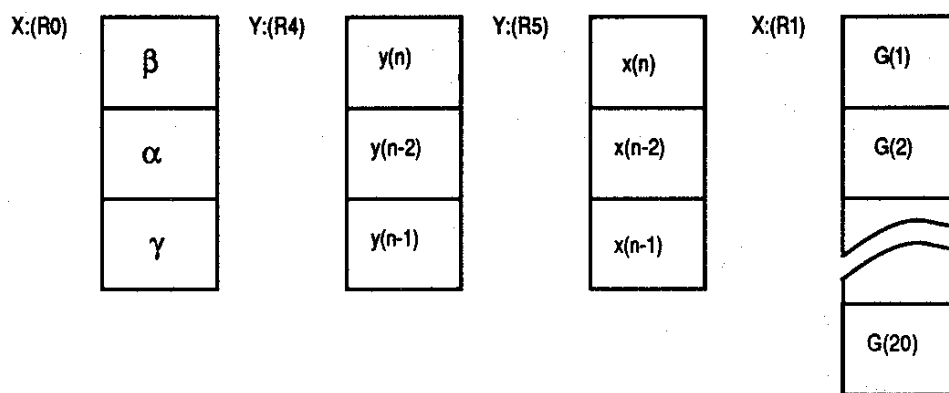


Figure 10. IIR Filter Data Structures

The theoretically minimum execution time is determined by the number of terms in the difference equation (four in this case), which equate to the number of multiply/accumulates necessary to calculate y(n). The actual execution time depends how the data is stored, indexed, and manipulated, which is largely application dependent. The following code demonstrates the same filter done in four instructions (neglecting I/O). The tradeoff is in the number of data ALU registers used (see reference 5).

MOVE	X:ADC,Y1			
MPY	-X0,Y0,B	X:(R0)-,X0	B,Y0	;B = - $\beta y(n-2)$
MAC	X0,Y0,B	X:(R0)-,X0	Y1,Y:(R5)+	;B = B + $\gamma y(n-1)$
MAC	X0,Y1,B		Y:(R5),Y1	;B = B + $\alpha x(n)$
MACR	-X0,Y1,B	X:(R0)-,X0		;B = B - $\alpha x(n-2)$
MOVE	B,X:DAC			

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Register Y1 is now used in addition to X0 and Y0. Also, X0, Y0, and B must not be modified before the next call to this routine. Numerous ways exist to code the difference equation; it cannot be done in fewer instructions than the number of terms. The details are then up to tradeoff considerations for the remainder of the software system.

FINAL IMPLEMENTATION OF THE DSP56000/1 CODE

To construct a graphic equalizer, a set of 10 IIR bandpass filters are used in parallel for each of the stereo audio channels. Using 1 kHz as a starting point, successively dividing down by two to 31 Hz, and successively multiplying by two up to 16 kHz, a 10-band octave response is generated. The coefficients for the lower eight bands are easily determined by means of Equations (26) through (30). Equations (13), (14), (15), and (20) are used for the highest two bands. Unity gain at the center frequency is chosen, and a quality factor, Q , is arbitrarily selected to be 1.4. Table 1 lists the 10 sets of coefficients used to generate the response curves shown in Figure 11. The pole/zero plot of Figure 12 shows the location of the poles for all 10 bands. The response curve is not the final response of the system, but shows the response of each individual filter superimposed on the same graph. The total audio response would be the summation of each filter, where the gain of each can independently vary from g_{LO} to g_{HI} (where $g < 0$ represents a phase change of π).

Table 1. 10-Band Bandpass IIR Coefficients

Center Frequency	IIR Coefficients		
	α	β	γ
31	0.000787462865	0.498425074	0.998415336
62	0.00157244917	0.496855102	0.996816209
125	0.00316016172	0.493679677	0.993522095
250	0.00628062774	0.487438745	0.986812425
500	0.0124054279	0.475189144	0.972715729
1000	0.0242101804	0.451579639	0.941937749
2000	0.0461841095	0.407631781	0.871031797
4000	0.0845577687	0.330884463	0.699565951
8000	0.1199464	0.2601072	0.3176087
16000	0.159603	0.1800994	-0.4435172

The primary difference between the analog filter versus the digital response is the zero at $f_s/2$. Anything above this frequency is not allowed, because it would violate the basic sampling theorem that says all frequencies must be lower than half of f_s to prevent aliasing. This zero causes the higher frequency bands to be asymmetric over the logarithm of frequency. The SAA formulas derived previously must be used cautiously, or not at all, at these higher frequencies ($\theta > \pi/4$ or $f > f_s/8$). The exact formulas (Equations (13), (14), (15), and (20)) should be used at the high frequencies. Mathematically, this zero is the consequence of mapping $s = j\Omega$, the infinite axis, into the finite unit circle of the z -plane (Equation (3)). This zero at $\theta = \pi$ is the same zero found at $\Omega = \text{infinity}$ with the analog filter. As evidenced by the frequency warping (Equation (3b)), both the analog frequency, Ω , and the digital frequency, ω , start at zero, but as Ω approaches infinity, f approaches $f_s/2$. However, with the SAA, both the analog and digital frequencies are equal, since $\tan\theta \approx \theta$ for θ small.

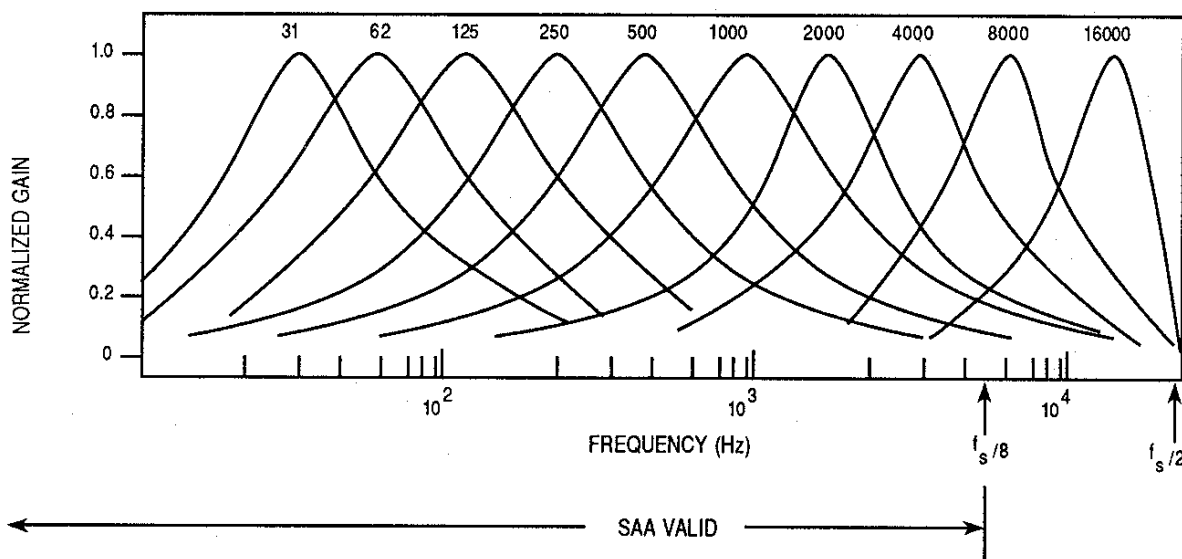


Figure 11. 10-Band Bandpass IIR Filter Response

Figure 13 shows the total algorithmic system for the graphic equalizer. Each block labeled F_i is one IIR filter; g_i is the gain coefficient set by the i^{th} potentiometer that scales F_i . Because of the direct through-path, the condition of all g_i 's equal to zero produces a flat response (the output is due only to the direct path from the input). The passthrough gain at 2^{-2} is required to scale the g_i 's so that g_i 's a fraction. All g_i 's equal to one will essentially produce a gain of five ($\sim +14$ dB). However, this gain will not be exactly flat since ripple is produced in the response curve due to the finite number and quality factor, Q , of each band (also true of analog equalizers). All g_i 's set to -0.2 will produce an overall gain of 0.2 (~ -14 dB); again there will be ripple in the response.

The scaling of the data, shown in Figure 13, is done for several reasons. First, the multiplication of the input data by 2^8 normalizes the data (the input is 16-bit data sign-extended to 24 bits). This technique will minimize word-length and roundoff error effects in the IIR blocks. Second, the left shift by two (2^2) after volume scaling compensates for the pass-through gain of 2^{-2} (normalizes the data) so that anything above 24 bits will be limited rather than truncated. The final multiplication by $1/256$ (2^{-8}) shifts the data back to its original 16-bit (sign-extended to 24-bit) format.

The execution time for each IIR block (as implemented in this example) is $0.7 \mu\text{s}$. For all 10 filters of one channel, the total time is $7 \mu\text{s}$. Adding in approximately $4 \mu\text{s}$ for volume scaling, limiting, receiving and transmitting to the SSI, etc. gives a total execution time of $11 \mu\text{s}$. Since the interrupt period is $(1/f_s \times 1/2) = 11.3 \mu\text{s}$, the control-panel polling portion of the software is executed for $0.3 \mu\text{s}$ for every $11.3 \mu\text{s}$. The ratio represents a duty cycle of two percent for slide potentiometer input and 98 percent for audio processing. However, this data cycle poses no problem in that the front panel settings are changed slowly with respect to the 44.1-kHz sample rate of the digital audio.

As discussed previously, the minimum number of instructions (thus, the minimum execution time) is four since the filters have only four coefficients (i.e., terms). Although the example described in this application note is not the minimum design, it was chosen for its simplicity. There are numerous ways to optimize the algorithm (at the expense of simplicity, memory, etc.) to approach the theoretical limit of $0.4 \mu\text{s}$ per IIR filter. The difference equation (Equation (8)), which is a direct form 1 representation, can be expressed in other forms such as direct form 2 (or the canonical direct).¹² Other forms have advantages, such as better stability due to roundoff or overflow, or may use less memory due

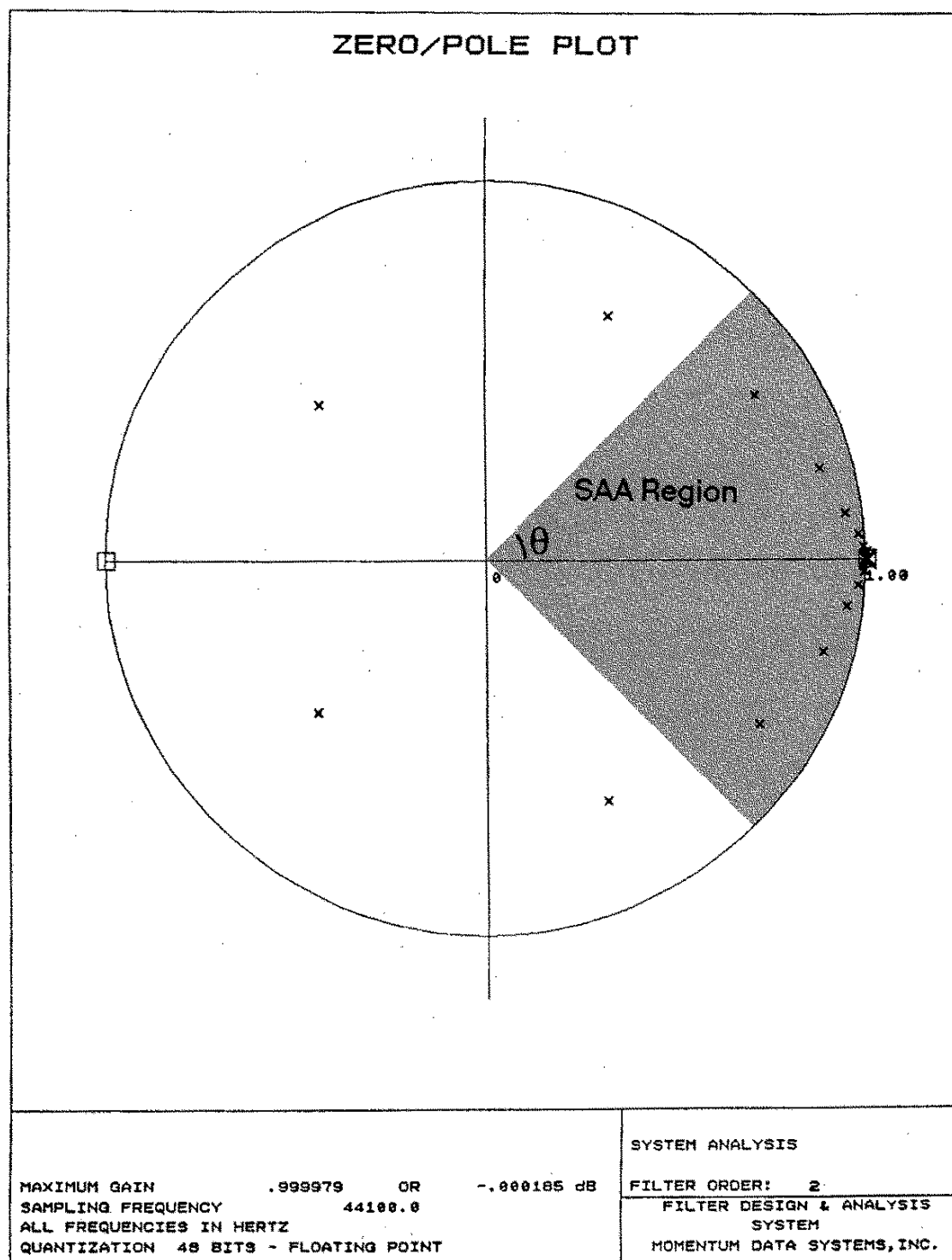


Figure 12. 10-Band Pole/Zero Plot

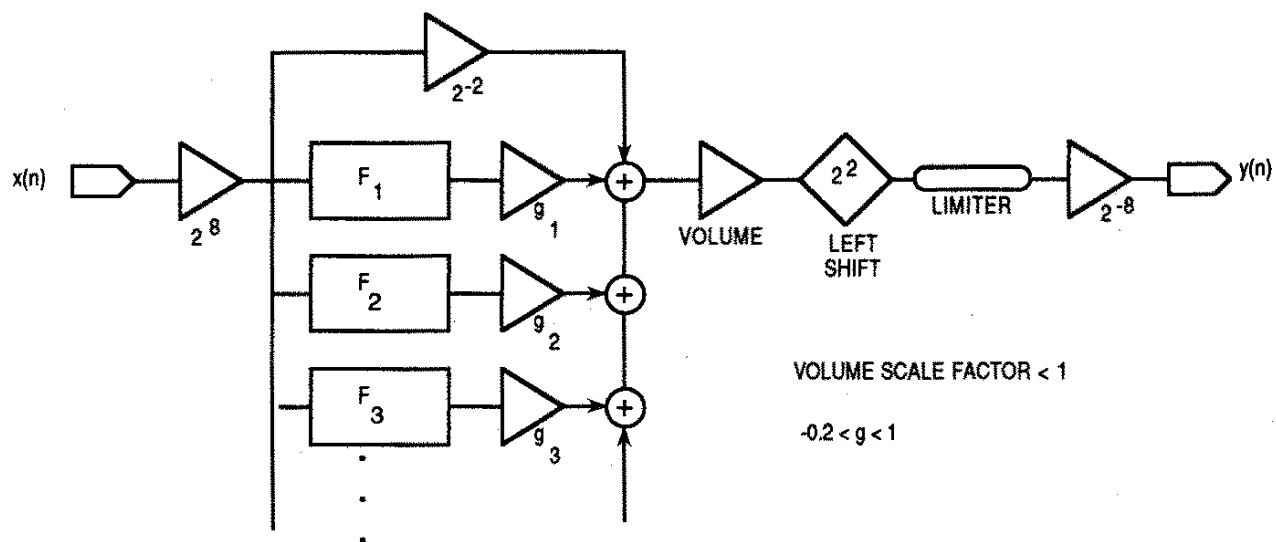


Figure 13. Data-Flow Diagram Showing Implementation of IIR Graphic Equalizer with the DSP56001

to storing filter states rather than storing input and output states. Regardless of the method used to implement the transfer function, the optimized execution time is simply the number of multiply/adds needed to calculate the difference equation. In practice, it may not be possible to approach this minimum because of addressing and data manipulation constraints. Because of the parallel moves allowed with the DSP56000/1, it is much easier to solve these indexing and data-move tasks. Generally, a good IIR design is one in which the total number of instructions is one plus the number of terms in the difference equation. This design allows one instruction cycle to set up data before beginning the MAC operations.

Flowcharts of the basic software algorithm that comprises the graphic equalizer are shown in Figure 14. The software is composed of two independent routines: the slide potentiometer scan routine and the sample/process interrupt routine. The scan routine (Figure 14(a)) scans 21 slide potentiometers, reduces the 8-bit value to 5 bits (to reduce the size of the lookup table), and uses that value as an index into a gain table. The value from the gain table is stored as the g_i 's for use by the sample/process routine. The slide potentiometer scan routine executes for approximately two percent of the total time.

Figure 14(b) shows the sample/process routine, which is executed via the SSI receive interrupt every 11.3 μ s. This routine consists of two nearly identical sections, one for left-channel and one for right-channel servicing. The channel requested is determined by the SC0 flag on the SSI port, which is tied directly to the CDP's LRCLK. Data is received from the SSI port, processed by the filter algorithm (previously shown in Figure 13), scaled by the volume control, and transmitted back to the CDP, all in less than the sample time window of 11.3 μ s. This routine is executed for 98 percent of the time.

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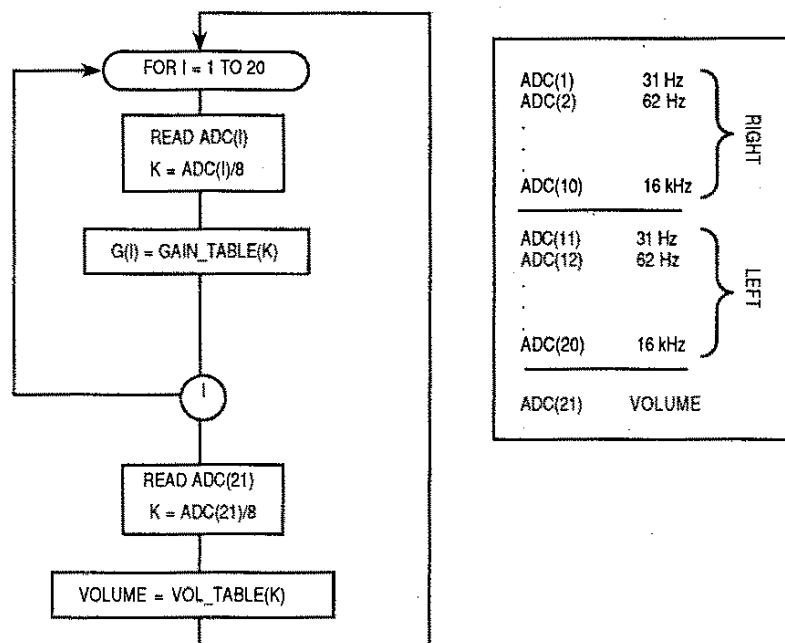


Figure 14(a). Algorithm Flowchart for Slide Potentiometer Scan Routine (Main Program)

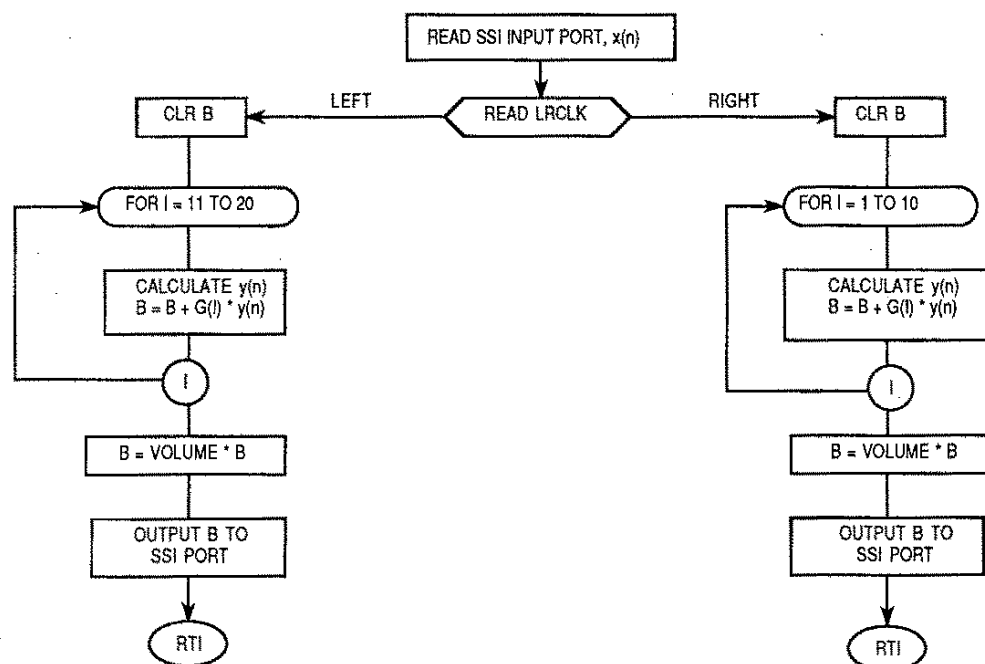


Figure 14(b). Algorithm Flowchart for CDP Interface and IIR Filter Processing (Interrupt Routine)

FOOTNOTES

- ¹"Filter Design & Analysis System," chp. 2, p. 15.
- ²Brophy, *Basic Electronics*, pp. 88-92.
- ³Lancaster, *Active Filter Cookbook*, pp. 10-18.
- ⁴Oppenheim and Schafer, *Digital Signal Processing*, pp. 206-211.
- ⁵Rabiner and Gold, *Theory and Application*, pp. 219-224.
- ⁶Oppenheim and Schafer, *Digital Signal Processing*, p. 210.
- ⁷Strawn, *Digital Audio Signal Processing*, pp. 117-126.
- ⁸Oppenheim and Schafer, *Digital Signal Processing*, pp. 8-15.
- ⁹Rabiner and Gold, *Theory and Application*, pp. 9-16.
- ¹⁰Strawn, *Digital Audio Signal Processing*, pp. 33-35.
- ¹¹*ibid.*, p. 116.
- ¹²Rabiner and Gold, *Theory and Application*, pp. 41-43.

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1. Brophy, J. J. *Basic Electronics for Scientists*. New York: McGraw-Hill, 1966.
2. Chrysafis, A. "Fractional and Integer Arithmetic." Motorola Application Note, forthcoming.
3. "Filter Design & Analysis System." Version 1.3, Momentum Data Systems, 1985.
4. Lancaster, D. *Active Filter Cookbook*. Indianapolis: Howard W. Sams & Co., Inc., 1975.
5. Lindsley, B. "Digital Filters on DSP56000/1." Motorola Application Note, forthcoming.
6. Oppenheim, A. V., and Schafer, R.W. *Digital Signal Processing*. New Jersey: Prentice-Hall, 1975.
7. Rabiner, L. R., and Gold, B. *Theory and Application of Digital Signal Processing*. New Jersey: Prentice-Hall, 1975.
8. Strawn, J., et al. *Digital Audio Signal Processing — An Anthology*. William Kaufmann, 1985.

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Motorola DSP56000 Macro Cross Assembler Version X112b 88-03-10 16:09:32 dgetxt.asm Page 1

```

1          page      132
2
3          ;*****
4          ;*****
5          ;*
6          ;*          DUAL 10-BAND IIR BAND-
7          ;*          PASS FILTER GRAPHIC EQUALIZER
8          ;*
9          ;*****
10         ;*****
11
12
13         ;*****
14         ;* SSI and other I/O EQUATES *
15         ;*****
16
17         00000040      START      EQU      $0040
18         0000FFFF      M_IPR      EQU      $FFFF
19         0000FFFE      M_BCR      EQU      $FFFE
20         0000FFEC      M_CRA      EQU      $FFEC
21         0000FFED      M_CRB      EQU      $FFED
22         0000FFE1      M_PCC      EQU      $FFE1
23         0000FFEE      M_SR       EQU      $FFEE
24         0000FFEF      M_TX       EQU      $FFEF
25         0000FFEF      M_RX       EQU      $FFEF
26
27
28         ;*****
29         ;* RESET VECTOR
30         ;*****
31
32         P:0000          ORG      P:$0000
33         P:0000 0C0040   JMP      START
34
35
36         ;*****
37         ;* SSI RCV INTERRUPT VECTOR *
38         ;*****
39
40         P:000C          ORG      P:$000C
41         P:000C 0BF080   JSR      LRTEST
42         0000F1
43
44         ;*****
45         ;* MAIN PROGRAM
46         ;*****
47
48         P:0040          ORG      P:START
49

```

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```

50      ;-----
51      ;   Mask Interrupts
52      ;-----
53      P:0040 0003F8      ORI      #$03,MR
54
55      ;-----
56      ;   Initialize SSI Port
57      ;-----
58      P:0041 08F4BE      MOVEP     #$3300,X:M_BCR      ;3 wait states for ADC and MUX.
59      003300
60      P:0043 08F4BF      MOVEP     #$3000,X:M_IPR      ;SSI RCV INT priority level.
61      003000
62      P:0045 08F4AC      MOVEP     #$6000,X:M_CRA      ;Set SSI word length = 24.
63      006000
64      P:0047 08F4AD      MOVEP     #$3200,X:M_CRB      ;Set SSI to synchronous,
65      003200
66
67      ;-----
68      ;   and enable RE and TE.
69      P:0049 08F4A1      MOVEP     #$01FF,X:M_PCC      ;Turn on SSI Port.
70      0001FF
71
72      ;-----
73      ;   Move constants from P:mem to X:mem and Y:mem
74      ;-----
75
76      P:004B 62F400      MOVE      #$18D,R2      ;** Filter Coefficients.
77      00018D
78      P:004D 332000      MOVE      #$20,R3
79
80      ;Table located at X:$20.
81      P:004E 061E80      DO        #30,COLOOP      ;Length of table = 30.
82      000051
83
84      P:0050 07DA84      MOVE      P:(R2)+,X0      ;Order is ... beta, alpha,
85      P:0051 445B00      MOVE      X0,X:(R3)+      ;gamma for each band.
86      COLOOP
87
88      P:0052 62F400      MOVE      #$1AB,R2      ;** Filter Gain Look-up.
89      0001AB
90      P:0054 334000      MOVE      #$40,R3
91
92      ;Table located at X:$40.
93      P:0055 062080      DO        #32,FGLOOP      ;Length of table = 32 (5 bits).
94      000058
95
96      P:0057 07DA84      MOVE      P:(R2)+,X0      ;Minimum value is -.2, maximum
97      P:0058 445B00      MOVE      X0,X:(R3)+      ;value is 0.999, center value is 0.
98      FGLOOP
99
100     P:0059 62F400      MOVE      #$1CB,R2      ;** Volume Gain Look-up.
101     0001CB
102     P:005B 336000      MOVE      #$60,R3
103
104     ;Table located at X:$60.
105     P:005C 062080      DO        #32,VGLOOP      ;Length of table = 32 (5 bits).
106     00005F
107
108     P:005E 07DA84      MOVE      P:(R2)+,X0      ;Minimum value is 0, maximum
109     P:005F 445B00      MOVE      X0,X:(R3)+      ;value is 0.9999.
110     VGLOOP
111
112     P:0060 62F400      MOVE      #$1EB,R2      ;** Mux Sel Address.
113     0001EB

```

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```

94      P:0062 330000      MOVE      #0,R3
95
96      P:0063 061580      DO      #21,MSLOOP      ;Table located at Y:$00.
          000066      ;Length of table = 21.
97      P:0065 07DA84      MOVE      P:(R2)+,X0      ;These are the MUX select addresses
98      P:0066 4C5B00      MOVE      X0,Y:(R3)+      ;for each of the 21 slide pots.
99      MSLOOP
100
101
102      ;-----
103      ;      Set runtime variables
104      ;-----
105      P:0067 44F400      MOVE      #$200000,X0      ;Constants used for data scaling.
          200000
106      P:0069 447000      MOVE      X0,X:>$1D
          00001D
107      P:006B 44F400      MOVE      #>$80,X0
          000080
108      P:006D 447000      MOVE      X0,X:>$1E
          00001E
109
110
111      ;-----
112      ;      Clear x(n) and y(n) table arrays
113      ;-----
114      P:006F 200013      CLR      A      ;Clear Y:$20 to Y:$BF.
115      P:0070 322000      MOVE      #$20,R2
116
117      P:0071 06A080      DO      #$A0,XYNCLR      ;This area is used for runtime
          000073      ;tables, x(n) and y(n).
118      P:0073 5E5A00      MOVE      A,Y:(R2)+      ;X:$20..$22 - x(n) left chan.
          XYNCLR      ;X:$40..$42 - y(n) left chan. 31 Hz.
119      ;X:$44..$46 - y(n) left chan. 62 Hz.
120      ; ....
121      ;X:$60..$62 - y(n) left chan. 16 kHz.
122
123
124      ;X:$30..$32 - x(n) right chan.
125      ;X:$80..$82 - y(n) right chan. 31 Hz.
126      ;X:$84..$86 - y(n) right chan. 62 Hz.
127      ; ....
128      ;X:$A0..$A2 - y(n) right chan. 16 kHz.
129
130
131      ;-----
132      ;      Clear g(n) and SP(n) arrays
133      ;-----
134      P:0074 200013      CLR      A      ;Clear X:$00 to X:$14.
135      P:0075 320000      MOVE      #0,R2      ;This is gain array which contains
136      ;fractional gain value from look-up
137      P:0076 061580      DO      #21,GNCLR      ;table used to scale filtered band.
          000078
138      P:0078 565A00      MOVE      A,X:(R2)+
          GNCLR
139      P:0079 328000      MOVE      #$80,R2      ;Clear X:$80 to X:$94.
140      ;This is 8-bit value read from
141      ;ADC slide pots. This value when
142      P:007A 061580      DO      #21,SNCLR

```

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```

00007C
143 P:007C 565A00 MOVE A,X:(R2)+ ;reduced to 5 bits is used as an
144 SWNCLR ;index into gain lookup table at
145 ;X:$40. The value from lookup table
146 ;is a 24-bit fraction which is stored
147 ;at X:$00..$X:$14.
148
149
150 ;-----
151 ; Setup Register Defaults for Interrupt Routines
152 ;-----
153
154 P:007D 344000 MOVE #$40,R4 ;** Yi(n):L-ch
155 P:007E 3C0400 MOVE #4,N4
156 P:007F 368000 MOVE #$80,R6 ;** Yi(n):R-ch
157 P:0080 3E0400 MOVE #4,N6
158 P:0081 352000 MOVE #$20,R5 ;** X(n):L-ch
159 P:0082 0502A5 MOVE #2,M5
160 P:0083 373000 MOVE #$30,R7 ;** X(n):R-ch
161 P:0084 0502A7 MOVE #2,M7
162
163 P:0085 302000 MOVE #$20,R0 ;** IIR Coeff
164 P:0086 051DA0 MOVE #29,M0
165 P:0087 330000 MOVE #0,R3 ;** Gain Coeff
166 P:0088 0514A3 MOVE #20,M3
167 P:0089 3B8000 MOVE #$80,N3
168
169
170 ;-----
171 ; Init SSI Interrupt
172 ;-----
173 P:008A 08F4AD MOVEP #$B200,X:M_CRB ;Enable SSI (RIE) interrupt.
174 P:008C 00FCB8 ANDI #$FC,MR ;Unmask all interrupts.
175
176
177 ;-----
178 ; Main Loop to Monitor Slide Pots
179 ;-----
180
181 P:008D 324000 LOOP1 MOVE #$40,R2 ;R2 points to gain lookup table.
182
183 P:008E 061580 DO #21,BPCHAN ;Scan all 21 pots.
184 P:0090 4FE300 MOVE Y:(R3),Y1 ;MUX select address of pot.
185
186 P:0091 4F7000 MOVE Y1,Y:$8000 ;Select MUX channel.
187 P:0093 06C880 DO #200,ADC_RD1 ;Wait for analog MUX to stabilize.
188 P:0095 000000 NOP
189 ADC_RD1
190
191 P:0096 5FF000 MOVE Y:$1000,B ;WR strobe to ADC (starts data
192 P:0098 000000 NOP ;conversion).

```

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```

193 P:0099 000000 NOP ;Note: A15 tied to WR of ADC.
194 P:009A 5FF000 MOVE Y:$8000,B
      008000
195 P:009C 06F481 DO #500,ADC_RD2 ;Wait for conversion ADC conversion.
      00009E
196 P:009E 000000 NOP
      ADC_RD2
197
198
199 P:009F 20001B CLR B
200 P:00A0 5FF000 MOVE Y:$8000,B ;Read slide pot data from ADC.
      008000
201
202 P:00A2 45F400 MOVE #>$FF,X1 ;Mask off upper 16 bits.
      0000FF
203 P:00A4 20006E AND X1,B
204 P:00A5 21A500 MOVE B1,X1 ;X1 now contains 8-bit pot value.
205
206 P:00A6 47E800 MOVE X:(R3+N3),Y1 ;Previous pot value.
207 P:00A7 20007C SUB Y1,B
208 P:00A8 20002E ABS B ;If absolute value of difference
209 P:00A9 47F400 MOVE #>9,Y1 ;is less than 9, then skip.
      000009
210
211 P:00AB 20007D CMP Y1,B ;Note: 9 is rather arbitrary.
212 P:00AC 0AF0AB JMI SKIP
      0000AF
213
214 P:00AE 456800 MOVE X1,X:(R3+N3) ;If greater than 9, then update
215 P:00AF 205800 SKIP MOVE (R3)+ ;X:($80+pot_index).
      BPCHAN ;This comparison eliminates jitter
216 ;about a point.
217 P:00B0 000000 NOP ;End of 21 pot scan.
218
219
220
221 P:00B1 061480 DO #20,BPCHAN2 ;For all pots except volume control.
      000000
222
223 P:00B3 45E800 MOVE X:(R3+N3),X1 ;Load X1 with slide pot value.
224 P:00B4 20AF00 MOVE X1,B
225
226 P:00B5 20002A ASR B ;Reduce to 5-bit value for gain
227 P:00B6 20002A ASR B ;table lookup.
228 P:00B7 20002A ASR B
229
230 P:00B8 218A00 MOVE B1,N2
231 P:00B9 000000 NOP
232 P:00BA 45EA00 MOVE X:(R2+N2),X1 ;Load X1 with fractional value
233 ;from table lookup.
234 P:00BB 57E300 MOVE X:(R3),B ;Compare gain fraction to previous
235 P:00BC 20006D CMP X1,B ;value in X:(R3).
236 P:00BD 0AF0AA JEQ NOCHNG ;Skip if no change.
      0000CF
237 P:00BF 0AF0A7 JGT NSLOPE ;If new value is greater than
      0000C9 ;previous value, go to negative
238 ;slope routine.
239

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240
241      P:00C1 47F400 PSLOPE  MOVE          #0.0001,Y1          ;Positive slope routine.
          000347
242      P:00C3 200078 PRAMP   ADD    Y1,B          ;Increment previous gain value
243      P:00C4 576300          MOVE          B,X:(R3)          ;by 0.0001 towards latest value
244                                     ;read from slide pot.
245      P:00C5 20006D          CMP    X1,B          ;Continue updating this value
246      P:00C6 0E90C3          JLT    PRAMP          ;until previous value exceeds
247                                     ;new value.
248      P:00C7 0AF080          JMP    NOCHNG          ;Exit positive slope routine.
          0000CF
249
250                                     ;Note: In the course of this loop,
251                                     ;the SSI interrupt will occur many
252                                     ;times, so that the band-pass
253                                     ;filter response gain will be ramped
254                                     ;smoothly to its new value. Thus,
255                                     ;clicking noises generated from a
256                                     ;coarse 5-bit gain table will be
257                                     ;eliminated.
258      P:00C9 47F400 NSLOPE  MOVE          #-0.0001,Y1          ;Negative slope routine.
          FFFCB9
259      P:00CB 200078 NRAMP   ADD    Y1,B          ;Same as above but negative ramp
260      P:00CC 576300          MOVE          B,X:(R3)          ;to new gain value.
261      P:00CD 20006D          CMP    X1,B
262      P:00CE 0E70CB          JGT    NRAMP
263
264      P:00CF 456300 NOCHNG  MOVE          X1,X:(R3)          ;Update gain table with latest value
265      P:00D0 205800          MOVE          (R3)+          ;read from slide pot.
266      BPCHAN2
267                                     ;Continue for the all 20 of the
268                                     ;band-pass slide pots.
269
270      P:00D1 326000 VOLUME  MOVE          #$60,R2          ;Pot 21 (volume) is treated
271      P:00D2 57F000          MOVE          X:$94,B          ;seperately since it uses a different
          000094
272      P:00D4 20002A          ASR    B          ;gain lookup table.
273      P:00D5 20002A          ASR    B          ;Reduce 8-bit value from ADC volume
274      P:00D6 20002A          ASR    B          ;slide pot to 5-bits.
275
276      P:00D7 21BA00          MOVE          B1,N2          ;Use this value for index into
277      P:00D8 000000          NOP          ;lookup table.
278      P:00D9 45EA00          MOVE          X:(R2+N2),X1      ;X1 now contains volume gain
279                                     ;fraction.
280      P:00DA 5F9E00          MOVE          Y:$1E,B          ;Y:$1E is previous value of volume
281      P:00DB 20006D          CMP    X1,B          ;gain.
282      P:00DC 0AF0AA          JEQ    NOCHNG2          ;If it has not changed, jump.
          0000EE
283      P:00DE 0AF0A7          JGT    NSLOPE2          ;If it is different, decide whether
          0000E8
284
285      P:00E0 47F400 PSLOPE2  MOVE          #0.00005,Y1        ;to ramp negative or positive.
          0001A3          ;Positive slope routine for volume.
286      P:00E2 200078 PRAMP2  ADD    Y1,B          ;Increment previous value by 0.00005
287      P:00E3 5F1E00          MOVE          B,Y:$1E          ;towards new value until it has
288      P:00E4 20006D          CMP    X1,B          ;passed new value. Then exit loop.

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289      P:00E5 0E90E2      JLT      PRAMP2      ;Note: As before, this loop will be
290                                          ;interrupted many times by the SSI
291                                          ;receive flag full. The volume gain
292                                          ;stored at Y:$1E will ramp smoothly
293                                          ;towards its new value.
294      P:00E6 0AF080      JMP      NOCHNG2
295      0000EE
296      P:00E8 47F400      NSLOPE2      MOVE      #-0.00005,Y1      ;Negative slope routine for volume.
297      FFFE5D
298      P:00EA 200078      NRAMP2      ADD      Y1,B
299      P:00EB 5F1E00      MOVE      B,Y:$1E      ;Same as before, but ramps in the
300      P:00EC 20006D      CMP      X1,B      ;opposite direction.
301      P:00ED 0E70EA      JGT      NRAMP2
302
303      P:00EE 4D1E00      NOCHNG2      MOVE      X1,Y:$1E      ;Update volume gain value with
304      P:00EF 205B00      MOVE      (R3)+      ;newest value read from slide pot.
305
306      P:00F0 0C008D      JMP      LOOP1      ;Do everything all over again...
307                                          ;continuing slide pot scan loop.
308
309
310      ;*****
311      ; MAIN INTERRUPT ROUTINE *
312      ;*****
313
314      P:00F1 0AAEAD      LRTEST      JSET      #0,X:M_SR,RIGHT      ;Check SC0 (LRCLK from CDP) to
315      000114                                          ;determine which channel to process.
316
317      ;*****
318      ; LEFT CHANNEL SERVICE *
319      ;*****
320
321      ;Save registers
322
323      P:00F3 491F00      LEFT      MOVE      B,L:$1F      ;Save register B.
324
325      ;Recieve data
326      P:00F4 084F2F      MOVEP      X:M_RX,B      ;Read SSI data.
327
328      P:00F5 21E600      MOVE      B,Y0      ;Copy SSI data to Y0.
329      P:00F6 0502A4      MOVE      #2,M4      ;Set y(n) modulo for 3 words.
330      P:00F7 310A00      MOVE      #10,R1      ;Set R1 index to filter gain values
331                                          ;for the left channel.
332
333      P:00F8 449E13      CLR      A      X:$1E,X0      ;X:$1E = $000080
334      P:00F9 205CD8      MPY      X0,Y0,B      (R4)+      ;Scale input data
335      P:00FA 596500      MOVE      B0,Y:(R5)      ;by 2^16.
336      P:00FB 0008F8      ORI      #$08,HR      ;Set scale mode to
337                                          ;scale up (left
338                                          ;shift) when data is
339                                          ;moved from B to X0.

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340 ;-----
341 ; All 10 Filters ...
342 ;-----
343 P:00FC 060A80 DO #10,LFBAND ;For all 10 bands of
    000104 ;left channel.
344 ;
345 P:00FE F0981B CLR B X:(R0)+,X0 Y:(R4)+,Y0 ;X0=beta;Y0=y(n-2).
346 P:00FF F088DE MAC -X0,Y0,B X:(R0)+,X0 Y:(R5)+,Y0 ;X0=alpha;Y0=x(n).
347 P:0100 4ED5DA MAC X0,Y0,B Y:(R5)-,Y0 ;X0=alpha;Y0=x(n-2).
348 P:0101 F098DE MAC -X0,Y0,B X:(R0)+,X0 Y:(R4)+,Y0 ;X0=gamma;Y0=y(n-1).
349 P:0102 46D9DB MACR X0,Y0,B X:(R1)+,Y0 ;Y0=gain for scaling.
350 P:0103 1B5C00 MOVE B,X0 B,Y:(R4)+ ;X0=filter response.
351 P:0104 204CD2 MAC X0,Y0,A (R4)+W4 ;A=scaled response.
352 LFBAND ;Continue for all
353 ;10 left chan bands.
354 ;
355 P:0105 00F7B8 ANDI #F7,MR ;Turn off scale mode.
356 P:0106 052BA4 MOVE #43,W4 ;Set Yi(n) modulo to wrap around to
357 ;start of entire y(n) buffer.
358 ;-----
359 ; Volume Scaling
360 ;-----
361 P:0107 449D00 MOVE X:$1D,X0 ;X:$1D=$200000.
362 P:0108 4EDD00 MOVE Y:(R5)+,Y0 ;Y0=x(n).
363 P:0109 4E9ED2 MAC X0,Y0,A Y:$1E,Y0 ;scale x(n) down
364 P:010A 21C400 MOVE A,X0 ;by 2^-2. Add this
365 ;in to the total
366 ;filter response.
367 P:010B 2000D8 MPY X0,Y0,B ;Y0=volume gain.
368 ;Scale total left
369 ;data by volume.
370 P:010C 204C3A ASL B (R4)+W4
371 P:010D 20003A ASL B ;Scale result by
372 ;2^2.
373 P:010E 18F400 MOVE B,X0 #>$8000,Y0 ;Now, move B to X0
    008000 ;to force limiting.
374 P:0110 2000D8 MPY X0,Y0,B ;Scale result down
375 ;by 2^-8.
376 ;-----
377 ; Output Data to CD Player
378 ;-----
379 ;
380 P:0111 08CF2F LXMIT MOVEP B,X:M_TX ;Write result to SSI.
381 ;
382 P:0112 499F00 MOVE L:$1F,B ;Retrieve B register and return.
383 P:0113 000004 RTI
384 ;
385 ;
386 ;*****
387 ; RIGHT CHANNEL SERVICE *
388 ;*****
389 ;
390 P:0114 491F00 RIGHT MOVE B,L:$1F ;Right channel process
391 ;identical to Left channel,
392 P:0115 084F2F MOVEP X:M_RX,B ;except right channel index

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393      P:0116 21E600      MOVE      B,Y0      ;registers (R6 and R7), and
394      P:0117 0502A6      MOVE      #2,M6      ;first 10 gain table values
395      P:0118 310000      MOVE      #0,R1      ;are used instead.
396
397      P:0119 449E13      CLR      A      X:$1E,X0
398      P:011A 205ED8      MPY      X0,Y0,B      (R6)+
399      P:011B 596700      MOVE      B0,Y:(R7)
400      P:011C 0008F8      ORI      #$08,MR
401
402      ;-----
403      ;      All 10 Filters ...
404      ;-----
405      P:011D 060A80      DO      #10,RFBAND
406      P:011F F0D81B      CLR      B      X:(R0)+,X0      Y:(R6)+,Y0
407      P:0120 F0F8DE      MAC      -X0,Y0,B      X:(R0)+,X0      Y:(R7)+,Y0
408      P:0121 4ED7DA      MAC      X0,Y0,B      Y:(R7)-,Y0
409      P:0122 F0D8DE      MAC      -X0,Y0,B      X:(R0)+,X0      Y:(R6)+,Y0
410      P:0123 46D9DB      MACR      X0,Y0,B      X:(R1)+,Y0
411      P:0124 185E00      MOVE      B,X0      B,Y:(R6)+
412      P:0125 204ED2      MAC      X0,Y0,A      (R6)+N6
413      RFBAND
414
415      P:0126 00F7B8      ANDI      #$F7,MR
416      P:0127 052BA6      MOVE      #43,M6
417
418      ;-----
419      ;      Volume Scaling
420      ;-----
421      P:0128 449D00      MOVE      X:$1D,X0
422      P:0129 4EDF00      MOVE      Y:(R7)+,Y0
423      P:012A 4E9ED2      MAC      X0,Y0,A      Y:$1E,Y0
424      P:012B 21C400      MOVE      A,X0
425      P:012C 2000D8      MPY      X0,Y0,B
426
427      P:012D 204E3A      ASL      B      (R6)+N6
428      P:012E 20003A      ASL      B
429
430      P:012F 18F400      MOVE      B,X0      #>$8000,Y0
431      P:0131 2000D8      MPY      X0,Y0,B
432
433      ;-----
434      ;      Output Data to CD Player
435      ;-----
436
437      P:0132 08CF2F      RXMIT      MOVEP      B,X:M_TX
438
439      P:0133 499F00      MOVE      L:$1F,B
440      P:0134 000004      RTI
441
442

```

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```

443 ;*****
444 ;* DATA VARIABLES and CONSTANTS *
445 ;*****
446
447 P:018D          ORG      P:$18D
448
449 ;-----
450 ;   IIR Coefficients
451 ;-----
452
453 ; 31 Hz
454         DC      .4984587          ;beta
455         DC      .0007706594       ;alpha
456         DC      .9984491          ;gamma
457
458 ; 62 Hz
459         DC      .496876
460         DC      .001562013
461         DC      .9968368
462
463 ; 125 Hz
464         DC      .4937405
465         DC      .003129769
466         DC      .9935817
467
468 ; 250 Hz
469         DC      .4876357
470         DC      .006182143
471         DC      .9870087
472
473 ; 500 Hz
474         DC      .4757282
475         DC      .01213592
476         DC      .9732514
477
478 ; 1000 Hz
479         DC      .4531951
480         DC      .02340247
481         DC      .9435273
482
483 ; 2000 Hz
484         DC      .4128511
485         DC      .04357446
486         DC      .8760584
487
488 ; 4000 Hz
489         DC      .3474929
490         DC      .07625358
491         DC      .7136286
492
493 ; 8000 Hz
494         DC      .2601072
495         DC      .1199464
496         DC      .3176087
497
498 ; 16000 Hz
499         DC      .180994
500         DC      .159503
501         DC      -.4435172

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495	;-----	
496	; Filter Gain (G) Coefficients	
497	;-----	
498		
499	DC	-0.200
500	DC	-0.187
501	DC	-0.171
502	DC	-0.160
503	DC	-0.150
504	DC	-0.137
505	DC	-0.114
506	DC	-0.103
507		
508	DC	-0.092
509	DC	-0.080
510	DC	-0.067
511	DC	-0.051
512	DC	-0.039
513	DC	-0.027
514	DC	-0.015
515	DC	0.000
516		
517	DC	0.000
518	DC	0.030
519	DC	0.060
520	DC	0.090
521	DC	0.120
522	DC	0.150
523	DC	0.180
524	DC	0.210
525		
526	DC	0.250
527	DC	0.290
528	DC	0.340
529	DC	0.380
530	DC	0.460
531	DC	0.540
532	DC	0.750
533	DC	0.999
534		
535	;-----	
536	; Volume Gain (V) Coefficients	
537	;-----	
538		
539	DC	0.0000
540	DC	0.0000
541	DC	0.0002
542	DC	0.0005
543	DC	0.0010
544	DC	0.0030
545	DC	0.0100
546	DC	0.0150
547		
548	DC	0.0200
549	DC	0.0300
550	DC	0.0400

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551	DC	0.0600
552	DC	0.0800
553	DC	0.1000
554	DC	0.1200
555	DC	0.1500
556		
557	DC	0.2000
558	DC	0.2500
559	DC	0.3000
560	DC	0.3500
561	DC	0.4000
562	DC	0.4500
563	DC	0.5000
564	DC	0.6000
565		
566	DC	0.7000
567	DC	0.8000
568	DC	0.9000
569	DC	0.9999
570	DC	0.9999
571	DC	0.9999
572	DC	0.9999
573	DC	0.9999

574		
575		
576	;-----	
577	; Slide Pot Addresses	
578	;-----	
579	DC	\$70
580	DC	\$71
581	DC	\$72
582	DC	\$73
583	DC	\$74
584	DC	\$75
585	DC	\$76
586	DC	\$77
587	DC	\$68
588	DC	\$69
589	DC	\$6A
590	DC	\$6B
591	DC	\$6C
592	DC	\$6D
593	DC	\$6E
594	DC	\$6F
595	DC	\$58
596	DC	\$59
597	DC	\$5A
598	DC	\$5B
599	DC	\$5C
600		
601	END	

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