CURTIS ELECTROMUSIC SPECIALTIES

CEM 3387

LOW NOISE V.C. SIGNAL PROCESSOR

Preliminary, January 1987

Description

The CEM 3387 is a general purpose audio signal processor intended for applications requiring high audio quality. Contained on-chip is a 3-pole low pass voltage controlled filter, cascaded to a 4-pole low pass V.C. filter with a voltage controlled feedback path for Q enhancement (resonance); also included is a final voltage controlled amplifier which drives two additional VCAs for voltage controlled pan into left and right outputs.

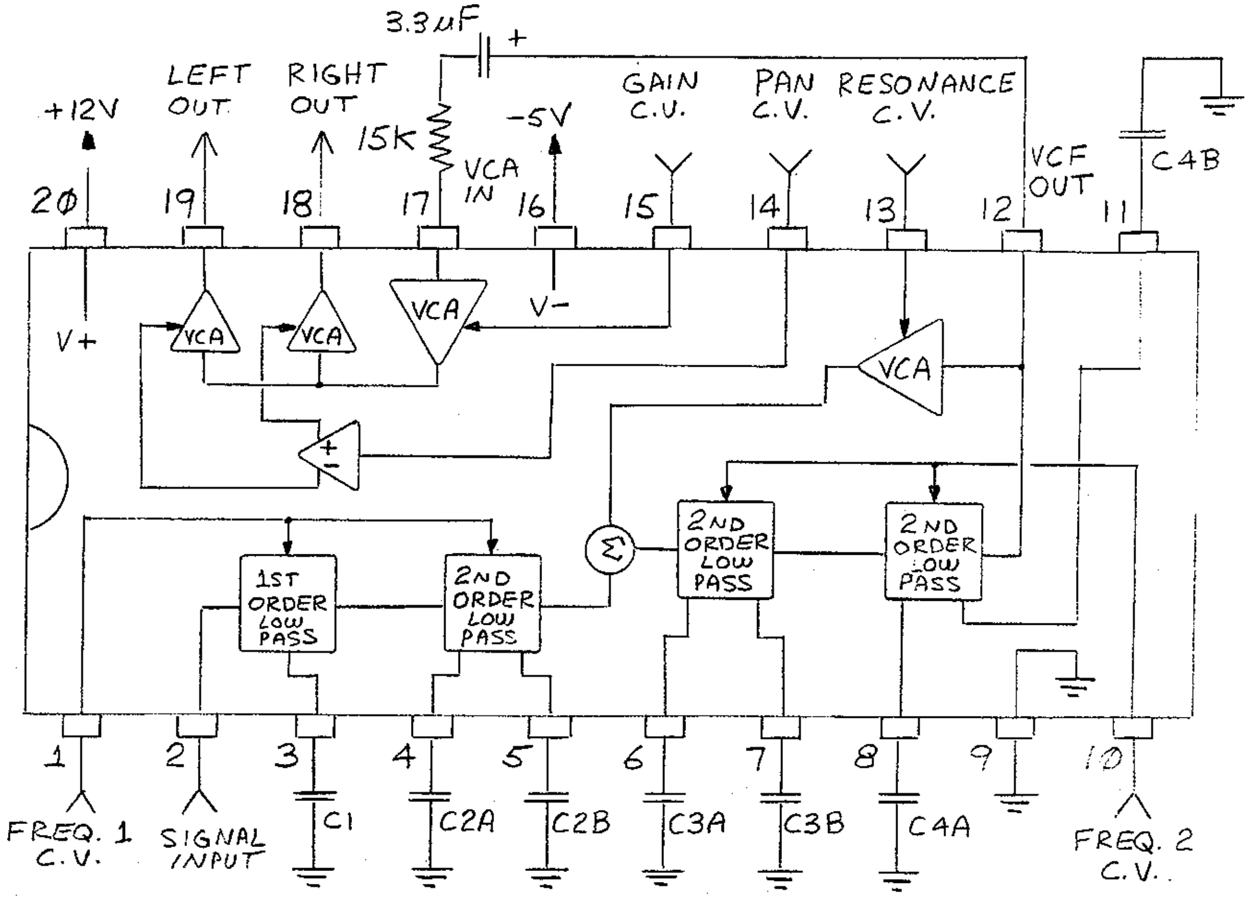
Each variable transconductor features very low noise and low distortion, for an overall system performance of better than 96dB signal-to-noise ratio and less than 0.1% THD. Easily interfaceable control voltage levels of 0 to +5 volts sweep the parameters over wide dynamic ranges -- 12 octaves for each of the two filters and 100 dB for the VCAs -- with negligible D.C. voltage shift at the outputs.

The use of second order filter sections to implement the two filters offers extensive applications flexibility. Through proper selection of capacitor ratios, the frequency and damping factor of each second order section may be independently selected. Thus Bessel, Butterworth, and Chebyshev responses of up to 7 poles may all be realized, making the 3387 suitable for antialiasing, reconstruction, and timbric control filters, or any combination of these. A 3-pole 1dB ripple Chebyshev reconstruction filter followed by a classical 4-pole musical instrument low pass filter with resonance is one example.

With its exceptionally low noise and low distortion, the CEM 3387 is the ideal choice for signal processing in CD compatible systems.

Features

- 7-pole V.C. LP Filter and 4 VCAs on Single Chip
- Extremely Low Noise: >96dB S/N ratio
- Low distortion: <0.1% THD
- Different Responses Possible: Bessel, Butterworth, Chebyshev, etc.
- Applications for Antialiasing, Reconstruction, & Timbric Control Variable Filters



CEM3387 LOW NOISE SIGNAL PROCESSOR

VCC = +12V VEE = -5V TA = 20°C

Parameter	Minimum	Typical	Maximum	Units
FILTER (3 pole & 4 pole)				
Signal Input for 0.1% THD	---	5.0	---	V.P.P.
Input Impedance	---	25	---	Kohm
Input D.C. Level	---	.63	---	V
Frequency Control Range for 0<VFREQ<+5V	---	10.5	---	octaves
Filter Stage Transimpedance at VFREQ = +5V	---	50	---	Kohm
Frequency Control Scale	---	2.3	---	oct/V
Frequency C.V. Input Bias	---	-0.1	---	uA
Tempco of Transimpedence at VFREQ = +5V	---	+1000	---	ppm
Tempco of Control Scale Factor	---	-3300	---	ppm
Signal to Noise Ratio re 5V.P.P. Output	---	96	---	dB
Control Feedthrough	---	±20	---	mV
Resonance C.V. for no feedback	---	+4.5	---	V
Resonance C.V. for sustained oscillation	---	+1.0	---	V
Resonance C.V. Input Bias	---	-0.4	---	uA/V
Output Impedance	---	0.1	---	ohm
Output Drive Capability	---	±1	---	mA
Max Output Voltage Swing	---	±3.5	---	V
VCA & PAN CONTROL				
Signal Input for 0.1% THD	---	±200	---	uA
Summing Node D.C. Level	---	-2.8	---	V
Max. Current Gain	---	1.0	---	
Gain C.V. For Max. Gain	---	+5.0	---	V
Gain C.V. for -96dB Gain	---	+0.1	---	V
Tempco of Gain at VGAIN = +5V	---	±500	---	ppm
Gain C.V. Input Bias	---	-0.4	---	uA/V
Signal to Noise Ratio for ±200uA Signal Input	---	100	---	dB
Control Feedthrough	---	±1	---	uA

Pan C.V. for -80dB Gain on Left Output	---	+.1	---	V
Pan C.V. for -80dB Gain on Right Output	---	+4.75	---	V
Pan C.V. for Equal Left and Right Outputs	---	+2.4	---	V
Pan C.V. Input Bias	---	-0.4	---	uA/V
Output Voltage Compliance	---	-0.5 to VCC -1.5	---	V
Positive Supply Range	+8	---	+15	V
Negative Supply Range	-4.5	---	-9	V
Supply Current	13	16	20	mA

NOTE: Control Voltage upper limits are ratiometric to the positive supply.

Power Supplies

As long as the maximum voltage between supply pins is maintained less than 24V the positive supply may be any voltage between +8 and +15V, while the negative supply voltage may be any value between -4.5 and -9. However, since the design was optimized for a negative supply of -5V, and since the total supply current is strongly influenced by the negative supply voltage (the already high power dissipation will approximately double at -9V), it is strongly recommended that the negative supply be kept in the -5 to -6V range.

The positive supply also affects several important parameters: all control voltages range from 0V to a maximum which is ratiometric to the positive supply at a factor of 5/12; thus for Vcc = +12V, the maximum control voltages are +5V (except frequency CV which can be higher; see below). In addition, the operating currents of the transconductors are ratiometric to the positive supply, and have been optimized at Vcc = +12V. Higher supply voltages will increase the noise and lower the distortion slightly, while decreasing the positive supply will will produce the opposite effects. Finally, the maximum signal handling capability before clipping is mostly a function of the positive supply, being approximately (7/12)Vcc - 0.5V.

Selection of Filter External Components

Since the filter is comprised of cascaded first and second order filter sections (see block diagram), it is easiest to consider each of the sections separately. The first order section has a low pass response given by

$$Vo = -Vin \frac{1}{Rcv1 \cdot C1 \cdot S + 1}$$

and hence a single pole at $w1 = 2\pi F = 1/(Rcv1 \cdot C1)$, where Rcv1 is an equivalent resistance ranging nominally from 50K to 200 Megohm and varied by the 3-pole filter control voltage applied to pin 1.

Each second order section (one in the 3-pole filter and 2 comprising the 4-pole filter) has a low pass response given by

$$Vo = -Vin \frac{1}{Rcv^2 \cdot Ca \cdot Cb \cdot S^2 + Rcv \cdot Ca \cdot S + 1}$$

where Ca and Cb are the external capacitors for each section with position as shown in the block diagram, and where Rcv is Rcv1 for the section in the 3-pole filter, but is Rcv2 for the two sections in the 4-pole filter, Rcv2 being controlled over a similar range by the voltage applied to pin 10.

Thus, the pole frequencies for these second order sections are:

$$wx = 2\pi Fx = 1/(Rcv\sqrt{Cxa\cdot Cxb})$$

and the damping factors for each are

$$dx = \sqrt{Cxa/Cxb} = 1/Q$$

where x denotes second order sections 2, 3, or 4.

A key feature of implementing the filter with cascaded second order sections is that different response types, such as Chebyshev, Bessel, and Butterworth, may be generated. This feature is accomplished by properly ratioing the filter section capacitors to each other to select specific damping factors and pole frequency ratios among all four sections.

The first case to consider is the equivalent response of cascaded first order sections, such as found in the classical musical instrument filters, where a 4-pole response is given by

$$Vo = Vin\ \frac{1}{(1 + S/wc)^4}$$

To generate such a response, the damping for each involved second order section must be set at 2, resulting in $Ca = 4 \times Cb$; the cut-off frequency for each second order section then becomes $Fc = 1/(4\pi Rcv\cdot Cb)$, and since all involved sections should have the same frequency, the Ca values should all be equal and the Cb values should all be equal to each other.
(e.g. $C3a = C4a = 4\cdot C3b = 4\cdot C4b$)

Another example is a 3-pole Chebyshev response with 1dB ripple, which would be qppropriate in applications where the 3-pole filter is used as a reconstruction filter. In such a case, the damping factor of the second order section is chosen at 0.5 and the pole frequency of the first order section is set at 0.5 times the pole frequency of the following second order section. Thus:

$$d2 = .5 = \sqrt{C2a/C2b} \text{ or } C2b = 4 \times C2a$$
$$w1 = 1/(Rcv1\cdot C1) = .5\ w2 = 1/(2\cdot Rcv1\cdot\sqrt{4\cdot C2a}) \text{ or } C1 = 4 \times C2a$$

This results in the cut-off frequency of the final response becoming $Fc = 1/(4\pi Rcv1\cdot C2a)$. (For simplicity of calculations, in this and subsequent examples, the cut-off frequency of a resulting Chebyshev response is assumed to be the same as the pole frequency of the final second order section, which in turn is very close to the frequency of the last peak in the response.)

A final example is a 7 pole Chebyshev response in an application as a variable antialiasing filter; in such a case involving both the 3-pole filter and 4-pole filter, it is assumed that transconductances of all sections are made equal by driving both control inputs with the same voltage so that $Rcv1 = Rcv2 = Rcv$. (In practice, a provision should be made to allow fine adjustment in the relative frequences of the 3-pole and 4-pole filters to accomodate any possible mismatches between sections.) For this 7-pole response, the damping factors and relative frequencies of the four sections are:

w1 = .206
w2 = .404   d2 = .771
w3 = .792   d3 = .317
w4 = 1.0   d4 = .092

The general procedure (which can be used for any number of poles and sections including the example above) is to first calculate the capacitor ratios within each second order section to generate the desired damping factor:

$$Cxb = \frac{1}{dx} \cdot Cxa$$

Then the ratios between Ca for the last section and Ca for all preceeding sections are calculated from the following:

$$Cxa = \frac{wr}{wx}\,\frac{dx}{dr} \cdot Cra$$

$$C1 = \frac{wr}{w1}\,\frac{1}{dr} \cdot Cra$$

Where the r denotes the values associated with the last section or reference section. For the above example, this results in the following ratios:

C1 = 52.8 C4a
C2a = 20.7 C4a ----- C2b = 1.68 C2a
C3a = 4.35 C4a ----- C3b = 10 C3a
C4b = 118 C4a

Again, the cut-off frequency of the overall response becomes $1/(21.7\pi\, Rcv \cdot C4a)$.

Once all the capacitor ratios have been calculated, the final step is to calculate the reference capacitor value (Cxa of the last section; i.e. Cra) from which all other values may be derived. The equivalent transconductor resistance, Rcv, is a function of the frequency control voltage as follows:

$$Rcv = 25K\,[\exp(.045(Vr - Vcf)/Vt) + 1]$$

where Vr = (5/12) Vcc, Vcf is the frequency control voltage affecting the particular Rcv (i.e. Vcf1 for Rcv1 and Vcf2 for Rcv2), and Vt = 28mV for an ambient temperature of 20°C. The 25K multiplier is a nominal value and has a tolerance of ±25%.

The equation shows that a) when the control voltage equals Vr, the nominal resistance is 50K, b) the control scale is approximately linear within ±1.3V of Vr producing a range of 8:1 (Rcv = 28K to 225K), and c) below Vr - 1.3 the scale is exponential at approximately 2.3 octaves per volt.
Thus, if a wide range with exponential scale is required (e.g. for the 4-pole filter as a music VCF), then the control voltage swing necessary to cover the full range is first considered: A ten octave range will require roughly 4.5V. Next, a convenient value for Vr and the lowest control voltage is selected: In this case, Vr should be 5V (Vcc = +12V) and 0V is chosen for the lowest control voltage (negative values for the frequency control voltage may be used for extended range). Finally, the equivalent Rcv value at the selected lowest control voltage is calculated, and from this, the value for the reference capacitor needed to provide the lowest desired frequency: At a control voltage of 0V, Rcv = 74.5 megohm, and for a corresponding lowest frequency of 16Hz in the music filter application,

$$Cb = 1/(4\pi 16\text{Hz}\ Rcv) = 68\text{pF}$$

resulting in Ca = 4 Cb = 270pF.

If only a narrow linear range is needed (in the antialiasing application, for example), then the filter should be controlled with voltage values restricted to around Vr. In this case, it is most convenient to first set the highest frequency at the point where Rcv is .55 times the value when the control voltage equals Vr, or 27.5K nominal (the absolute lowest value possible for Rcv is 25K nominal); this point corresponds to a control voltage of Vr + 1.44V.

Suppose the desired frequency range of the 7-pole filter is 5KHz to 40KHz. Then C4a is calculated at the highest frequency by:

$$C4a = 1/(21.7\pi\ 40\text{KHz} \cdot 27.5\text{K}) = 13.3\text{pF}$$

and the other capacitors become:

C1 = 702pF
C2a = 275pF C2b = 463pF
C3a = 58pF C3b = 579pF
C4a = 13pF C4b = 1569pF

In practice, all capacitors should be scaled down by 25% to allow for the possibility of the nominal resistance being 25% lower; then the control voltage may be trimmed so that the filter frequency covers the exact desired range.

Because of the very small value of C4a, much care must be exercised in the amount and repeatability of stray capacitance associated with the PC board and, if used, device socket.

Selection of VCA External Components

Since the VCA signal input is a current summing input at a voltage of -2.8V, an external series resistor and coupling capacitor are required between the input signal voltage and input pin (pin 17). To maintain better than 0.1% THD, the maximum input current should be limited to ±200uA; thus, the value of input resistor is:

$$Rin = Vinput\ (V.P.P.)\ /\ 400uA$$

The series coupling capacitor is then chosen to give the desired -3dB low frequency corner with the selected resistor.

The control scale is exponential from 0 to approximately +200mV, controlling the current gain form -100dB nominal to about -30dB. Thereafter the current gain increases in a linear fashion until it reaches the maximum of 0dB at Vr nominal. This slight rounded knee at the scale bottom allows an envelope to decay to zero with a natural exponential sound regardless of the small variations in VCA turn-on threshold.

The output current of this VCA internally drives the inputs to the two pan VCAs, which direct the output current to the left (pin 19) or right (pin 18) outputs. Since the device outputs are also currents with limited negative output voltage compliance (about -.5V), it is best to convert them to output voltages with a virtual ground summing op amp. When the input VCA is at maximum gain and its output panned all the way to one device output, the maximum output current will be nearly equal to the input current; hence the final maximum output voltage is given by:

$$Vo = Vin\ (Rf/Rin)$$

where Rf is the feedback resistor around the output op amp.

The gains of the two pan VCAs are complementary, being equal and half their maximum gain at a nominal control voltage of +2.5V. The control scales are linear between +.5V and +4.5V, becoming logarithmic beyond these extremes.

In a system with multiple CEM 3387s, only one op amp for each system output is needed, since the corresponding outputs of each device may simply be tied together before being converted to a voltage. Although limited, the device output voltage compliance is large enough to allow current splitting resistors to be used to form direct, unpanned outputs if desired: Such an application is shown in Figure 1, where the current splitting resistors (usually equal) are selected such that their parallel value times the maximum peak output current does not exceed .5 volt.

Although the noise in both input and pan VCAs is extremely low, it should be noted that the noise at the pan outputs is even lower (essentially zero) when the input VCA is off. This is because the current through each pan VCA is merely the output current of the input VCA; thus, when it is off, all currents through the pan VCAs are zero and the noise is also zero. In multi-channel systems this ensures extremely quiet system outputs when no channels are sounding.

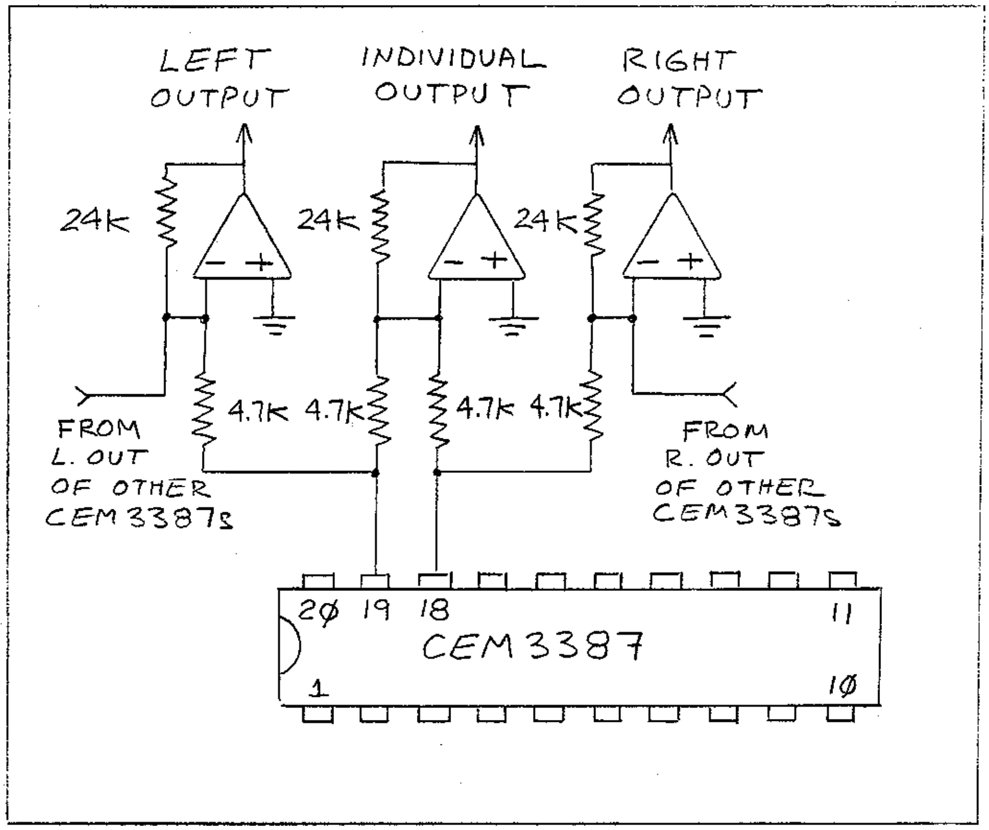


FIGURE 1: CONNECTION FOR DIRECT OUTPUT & COMBINED OUTPUTS FOR CEM3387