CURTIS ELECTROMUSIC SPECIALTIES

C E M 3 3 9 6

uP CONTROLLABLE DUAL WAVEFORM CONVERTER / PROCESSOR

Preliminary, June 1984 (Supersedes May, 1984)

Description

The CEM 3396 is a complete system for the generation and processing of audio waveforms in electronic musical instruments. Intended to be driven from digitally generated square or pulse timing signals, the device includes two independent waveform converters, a mixer for voltage controlling the relative balance between the two waveform converter outputs, a dedicated four-pole low-pass voltage controlled filter with voltage controllable resonance, a VCA for allowing one converter output to frequency modulate the filter, and two high quality output VCAs, one for envelope control and the other for dynamics and modulation effects. All eleven control inputs are high impedance, low bias current inputs which range from Ø to +5V, a feature which eliminates the usual Sample & Hold Buffers in a multiplexed DAC system.

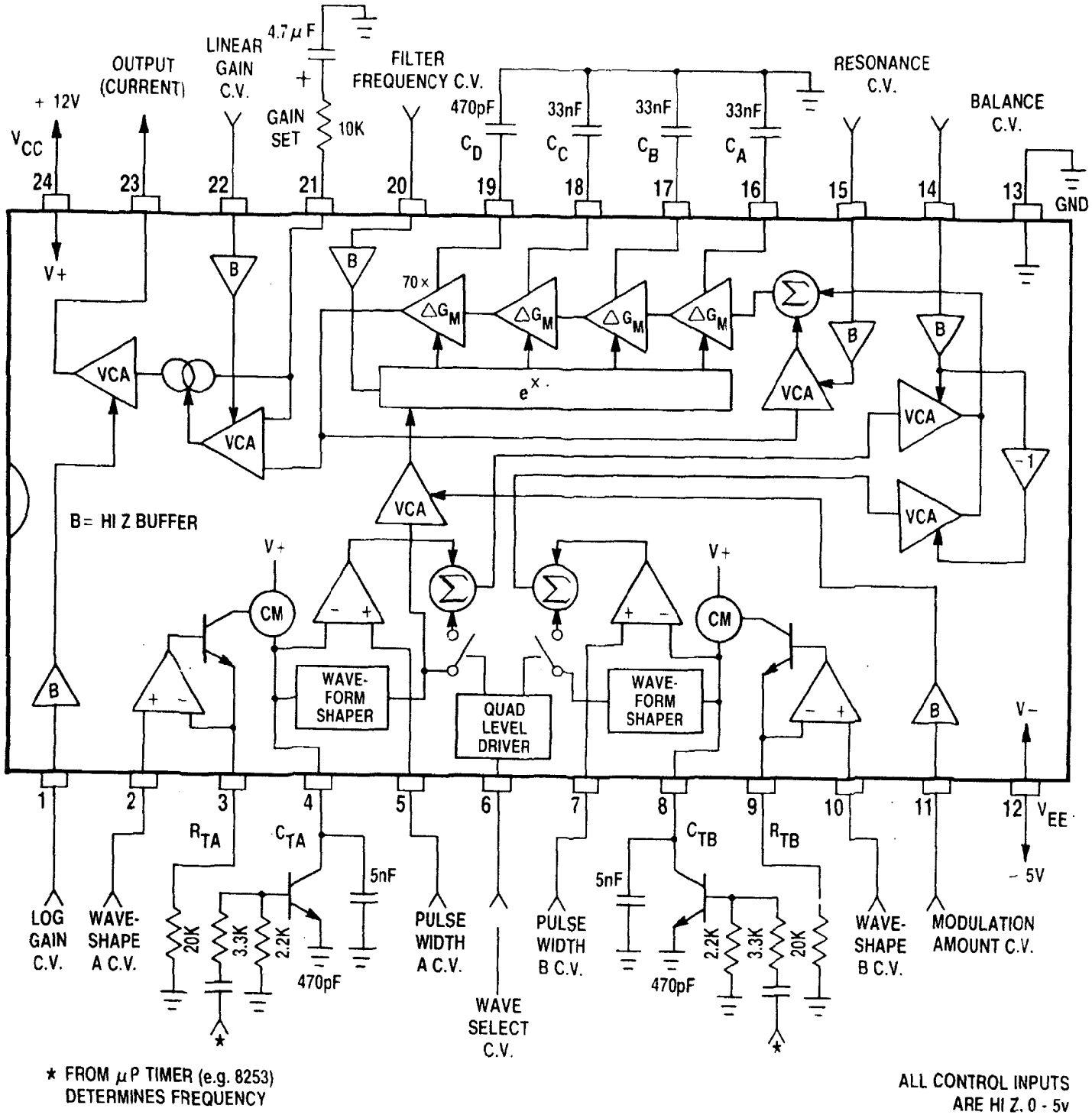
Each waveform converter is capable of forming numerous and continuously variable waveforms, including sawtooth, triangle, clipped triangle, and variable width pulse, and allowing various combinations of these to be selected. The frequency of these waveforms is equal to the input digital timing signal (typically generated by a programmable divider), allowing precise and stable control of pitch.

A unique feature of the low noise, low feedthrough filter keeps the peak-to-peak output level constant as the resonance is varied, producing a rich and full reasonance sound. The two series output VCAs offer additional flexibility with the choice of either linear or audio taper control scales. Special care has been taken in their design as well as the filter to ensure low intermodulation distortion for the clean processing of even complex waveform mixes. The VCA design at the same time offers low accumlative noise and very low control feedthrough without trimming for "click" free performance.

Requiring an absolute minimum of external components and support hardware, the CEM 3396 makes possible full featured professional sound in inexpensive musical instruments.

Features

- Complete Sound Synthesis System On-a-Chip: Two Multi-Waveform Converters, a 4-pole VCF, a VC Mixer, and Four VCAs
- Ø to +5V High Z Control Inputs for Direct Interface to CMOS Multiplexer from System DAC
- Few External Components
- Numerous Waveforms and Waveform Combinations Possible for More Timbral Variety than Previously Available
- Independent and Continuously Variable Waveshape and Pulse Width for each Converter
- Filter FM
- Constant Output v.s. Resonance VCF Characteristic
- Open Loop VCF Design for Rich Sound
- Low Noise, Low IM Destortion VCAs
- Choice of Linear or Audio Taper VCA Control Scales
- Low VCA Feedthrough Without Trimming



CEM3396 uP CONTROLLABLE DUAL WAVEFORM GENERATOR / PROCESSOR

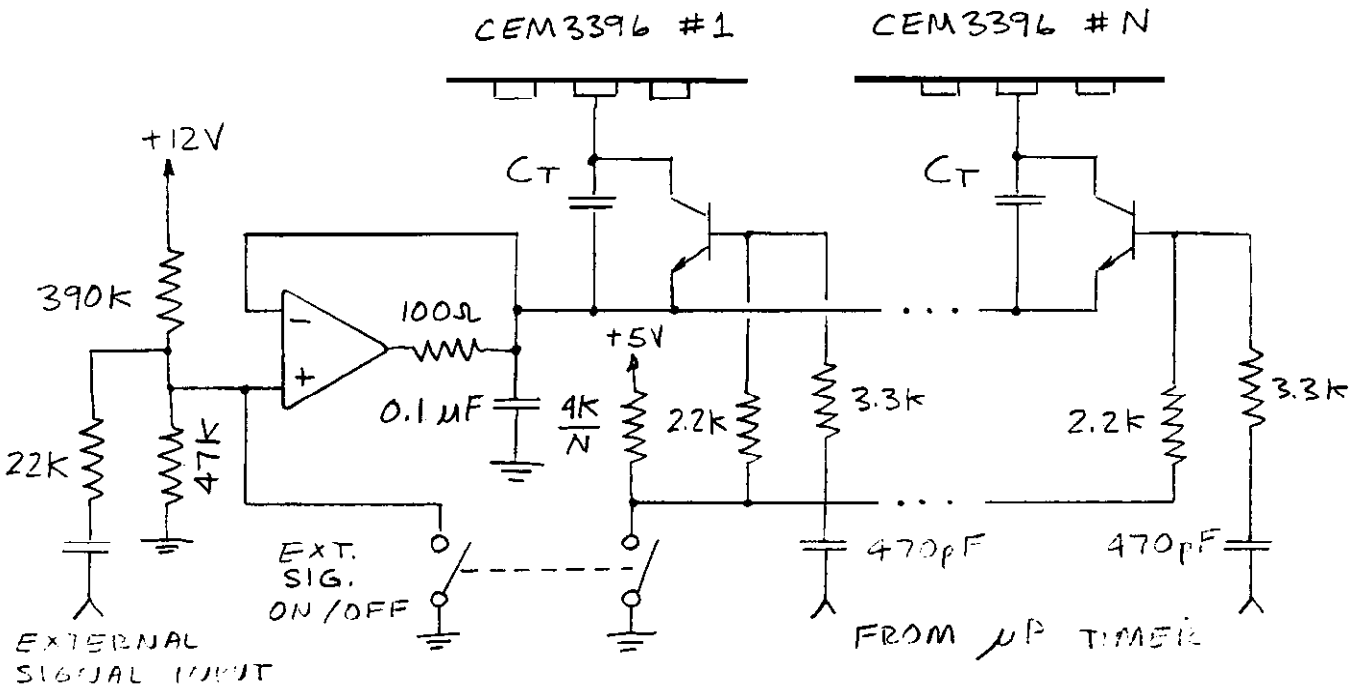


FIGURE 1: APPLICATION OF EXTERNAL SIGNAL

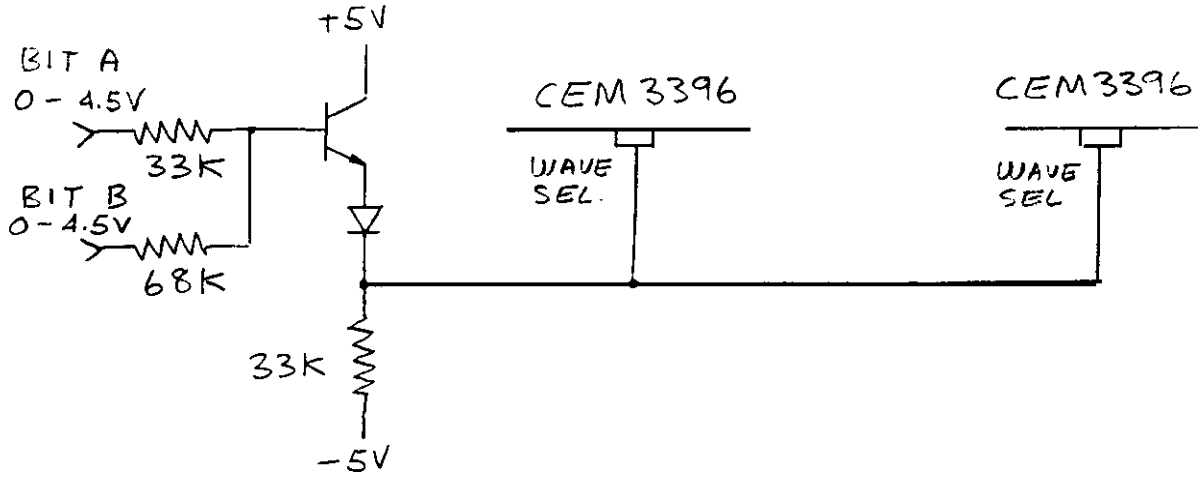


FIGURE 2: METHOD OF WAVEFORM SELECTION WITH TWO LOGIC LEVEL BITS

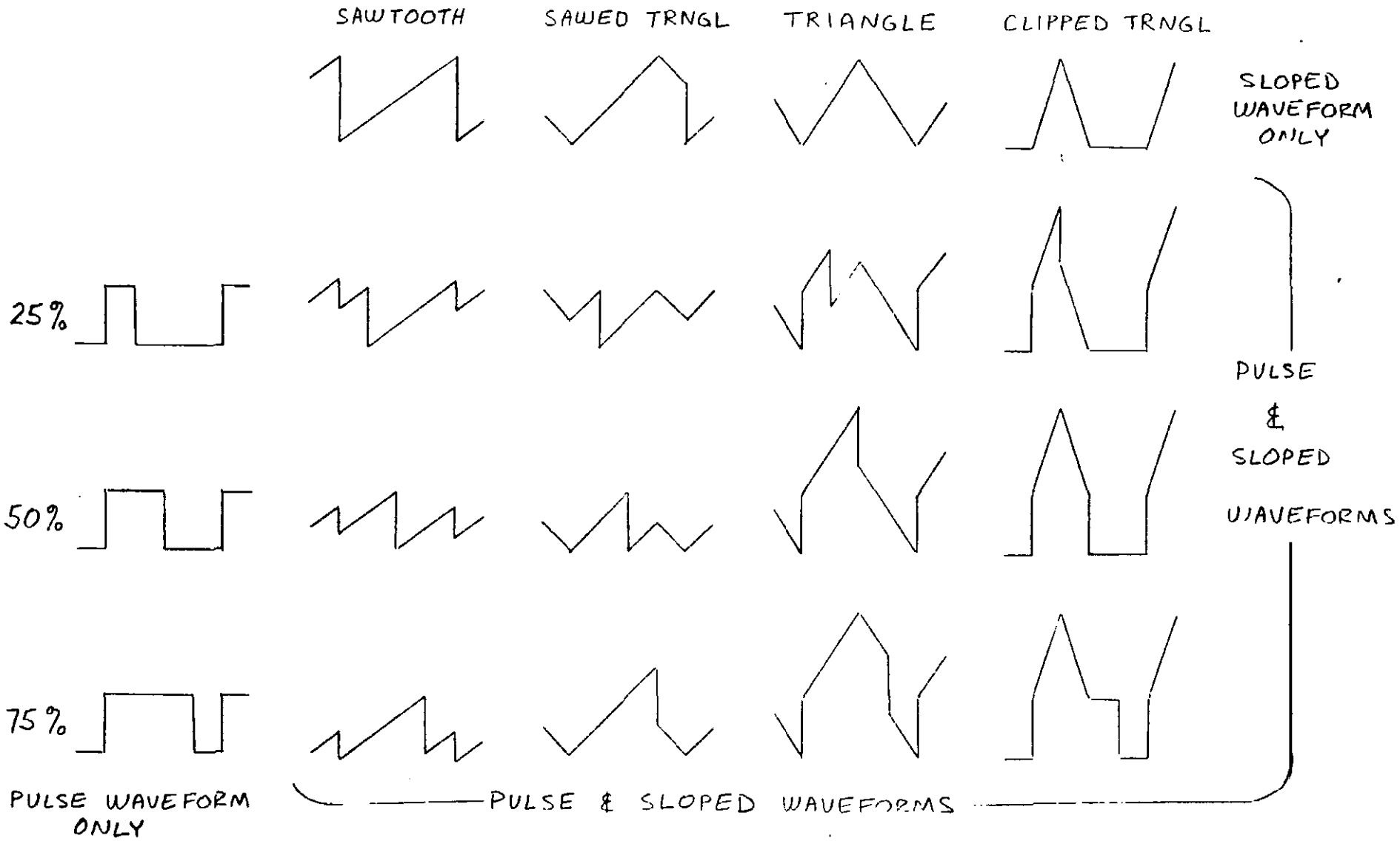
Vcc = +12V Vee = -5V Ta = 20 C Rgain = 6.8K

Parameter	Minimum	Typical	Maximum	Units
V/I CONVERTER				
Input Voltage Range	-2.5	---	+10.0	V
Output Current Range	0.003	---	1000	uA
Input Offset Voltage	---	±3	±7	mV
Output Offset Current 1	---	±1	±3	nA
Output Current Error 2	---	±3	±15	%
Conversion Linearity				
5 uA - 250 uA	---	±0.3	±1.5	%
250 nA - 250 uA	---	±1.5	±5	%
Waveshape C.V. Input				
Bias Current	---	±0.5	±3	nA
WAVEFORM SHAPER				
Input Low Voltage For Minimum				
Output 3	-20	0	+20	mV
Input Voltage for Maximum Output	+2.4	+2.5	+2.6	V
Input High Voltage For Minimum				
Output 3	+4.8	+5.0	+5.2	V
Pulse Width Comparator				
Offset Voltage	-12	0	+12	mV
Pulse Width C.V. Input				
Bias Current	---	±0.5	±3	nA
WAVEFORM SELECT				
Waveform Select Thresholds				
Converter A and B	---	---	<-.45	V
Converter B Only	-.45	-.30	-.15	V
None	+1.1	+1.3	+1.5	V
Converter A Only	+2.2	+2.6	+3.0	V
Wave Select C.V. Input				
Bias Current	---	-50	-300	nA
Wave Select C.V. Feedthrough 4				
Converter A Only	---	-30	-15	dB
Converter B Only	---	-30	-15	dB
Converter A and B	---	-25	-10	dB
FILTER MODULATOR				
Maximum Modulation Depth	.01X	---	2.0X	Freq.
Mod. C.V. for Max. Modulation	4.0	4.5	5.0	V
Modulation Amount for CV=0	---	1	5	%
Mod. C.V. Input Bias Current	---	-.07	-.4	nA/V

FILTER INPUT MIXER				
Mix. C.V. for 80 dB Attenuation of Converter A & Max. Converter B	-1.8	---	-2.2	V
Mix. C.V. for Max. Converter A & 80 dB Attenuation of Converter B	+1.8	---	+2.2	V
Mix. C.V. Input Bias Current	---	-.3	-2	nA
Mix. C.V. Feedthrough 5	---	-30	-15	dB
FOUR-POLE LOW-PASS FILTER				
Frequency Sweep Range	12	14	---	Octaves
Frequency C.V. Input Range	-2.5	---	+5.0	V
Frequency Control Scale, Midrange	-.47	-.50	-.53	V/octave
Frequency Scale Error 6	---	0.3	1.0	%
Temperature Coefficient of Scale	+3000	+3300	+3600	ppm
Frequency at C.V. = 0 (Ca = Cb = Cc = 33nF; Cd = 430pF)	500	700	980	Hz
Tempco of Frequency at C.V.=0	---	+500	---	ppm
Frequency C.V. Input Bias Current	---	-.5	-3	nA
Resonance Control Range	0dB	---	Oscillation	
Resonance C.V. for No Resance	0	---	+.3	V
Resonance C.V. for Oscillation	+3.5	+4.0	+4.5	V
V.P.P. Output Change from 0 to Max. Resonance	-2	0	+2	dB
Freq. Control Feedthrough 5,7	---	-30	-18	dB
Res. Control Feedthrough 5,8	---	-30	-10	dB
Signal to Noise Ratio 9	---	-93	-87	dB
TWO OUTPUT VCAS				
Linear Gain Control Input				
For 90 dB Attenuation 10	0	---	+.15	V
For Maximum Gain	+4.0	+4.5	+5.0	V
Audio Taper Gain Control Input				
For 90 dB Attenuation 10	0	---	+.3	V
For Maximum Gain	+4.0	+4.5	+5.0	V
Audio Taper Control Scale				
0V < C.V. < +3.3V	19	22	25	dB/V
+3.3V < C.V. < +5.0V	45	50	55	%/V
Control Voltage Feedthrough	---	0.3	2	uA
Signal to Noise Ratio 11	---	-96	-90	dB
Gain Set DC Voltage	-1	+1.3	+3.6	V
Output Voltage Compliance	Vee+1.6	---	Vcc-1.0	V
Maximum Output Current	---	---	±500	uA
POWER SUPPLIES				
Positive Supply Range 12	+11	---	+16	V
Negative Supply Range 12	-4.5	---	12.5	V
Positive Supply Current	12	15	18.5	mA
Negative Supply Current	9	12	15	mA

NOTES

Note 1: Current at Ct pin when Rt = ∞.
Note 2: Difference between current at Ct pin and current through Rt.
Note 3: Minimum output is defined as 1% of maximum output.
Note 4: With reference to the P.P. output voltage of selected waveform when switching from no waveforms at all.
Note 5: With reference to maximum P.P. output voltage generated by waveform converters.
Note 6: For Frequency Control Voltages between -1.5V and +2.5V. For voltage outside this range, maximum error increases to 8%.
Note 7: Over frequency C.V. range of -1.5V to +3.5V (10 octaves).
Note 8: Both converters are generating 50% duty cycle pulse waveforms.
Note 9: As measured at filter capacitor D pin with reference to maximum RMS signal voltage generated by waveform converters at that pin, and with cutoff frequency = 20KHz.
Note 10: With reference to maximum gain with other gain control voltage fixed at +5V.
Note 11: With reference to maximum RMS output voltage generated by waveform converters. Input to two VCAs is shorted to ground.
Note 12: Maximum supply across chip is 26V.



POSSIBLE WAVEFORMS FOR <u>EACH</u> WAVEFORM CONVERTER ON CEM3396

(PLEASE NOTE THAT BY DYNAMICALLY MODULATING PULSE WIDTH, SLOPED WAVESHAPE, OR BOTH, WAVESHAPE MODULATION BETWEEN ALL THESE WAVEFORMS IS POSSIBLE)

Power Supplies

The maximum supply allowed across the chip is 25 volts. The positive supply may range from +11V to +16V while the negative supply may range from -4.5 to -12.5V. Thus, +12V/-12V, +15V/-5V, and +12V/-5V would all be acceptable power supplies. For lowest warm-up and best performance, +12V/-5V supply is recommended.

Waveform Converters

Each waveform converter consists of a very linear voltage-to-current converter which charges capacitor Ct from Ø volts to some peak value, Vp. The capacitor is quickly discharged back to Ø volts every time the external computer-generated timing signal makes a low to high transistion. The brief discharge is generally accomplished by differentiating the digital timing signal with a capacitor and resistor and applying the resulting narrow pulse to the base or gate of an external NPN or N channel MOS transistor connected to the capacitor. (Open collector gates may also be used for this purpose).

The resulting sawtooth waveform generated across the capacitor is applied to one input of a comparator for generating a variable width pulse waveform, and to a waveform shaper for generating all sloped waveforms.

The waveform shaper operates as follows: From Ø to 5/24 Vcc (+2.5V for Vcc = +12V), the converter output increases minimum to maximum; from 5/24 Vcc to 5/12 Vcc (+5.ØV for Vcc = +12V), the output decreases from maximum back to minimum; and beyond 5/12 Vcc, the converter output remains at minimum. Thus, numerous waveforms may be produced simply by controlling the amplitude of the sawtooth generated across the capacitor Ct: a Ø to 5/24 Vcc sawtooth results in a sawtooth at the output while a Ø to 5/12 Vcc sawtooth produces a perfect triangle waveform at the output; asawtooth with a peak level between 5/24 and 5/12 Vcc generates a sawed-off triangle waveform which is very close to a mixture of sawtooth and triangle waveforms; and finally, a peak level greater than 5/12 Vcc results in a triangle waveform with the bottom flattened (clipped). Varying the peak level continuously over these voltages thus varies the waveshape continuously between these various waveshapes, adding more or less harmonics with different harmonic structures.

The peak level Vp of the sawtooth across Ct is determined by the period T between discharge pulses, the value of Ct, and the current charging Ct from the voltage to current converter, which in turn is simply the waveform control voltage Vwf divided by the conversion resistance, Rt.

$$Vp = \frac{Vwf * T}{Rt * Ct} = \frac{Vwf}{Rt * Ct * f}$$

For any given waveform, Vp must remain constant with frequency. Thus, as the frequency is changed, the waveform control voltage Vwf must be changed proportionately to keep the waveform unchanged. Conversely, for any given frequency, changing Vwf only will alter the waveshape.

To include all these variables in one easy expression, α is defined as a waveshape factor, and ranges from 1/2 to 2, where 1/2 is a sawtooth, 1 is a perfect triangle, and 2 is a clipped triangle with 50% duty cycle. Then the voltage Vwf required at any given frequency and waveshape is:

$$Vwf = F * Rt * Ct * 5/12 * Vcc * \alpha$$

The largest required voltage will be at the highest desired frequency and with a clipped triangle waveform ($\alpha = 2$), while the mimimum required voltage will occur at the lowest desired frequency and with a sawtooth waveform ($\alpha = 1/2$).

In a typical system, the waveform control voltage will be generated by a single DAC multiplexed with a CMOS multiplexer operating from a +5V supply, constraining the maximum value for Vwf to +5 volts. For best performance, the V/I converter charge current should be limited to 250uA. The conversion resistor therefore is 5V/250uA = 20K.

Suppose, for example, that the desired frequency range is 64Hz - 4.096 KHz (6 octaves), and Vcc = +12.0V. From the above equation, Ct would have to equal 6.1 nF, and the minimum required voltage would be approximately 20 mV.

At this low level, several sources of error must be taken into consideration. The most important is the input offset of the V/I converter. A 5mV offset with a 20mV input will generate a 25% error in the charge current. Thus the sawtooth at 64Hz will either be 25% lower in amplitude than it should be, or it will be 25% part triangle wave (not very noticeable). The triangle wave at 64 Hz (Vwf = 40 mV) will have a 12.5% error, resulting in a 12.5% sawtooth wave present in the triangle wave, or in its bottom clipped by 12.5% (more noticeable).

Other sources of error come from the DAC output offset voltage and differential non-linearity. A 1 LSB linearity error is 20 mV for an 8 bit DAC, 4.88 mV for a 10 bit DAC, and 1.22 mV for a 12 bit DAC.

As a practical matter, therefore, the maximum frequency range with a single conversion resistor is limited to about six octaves. For a wider range, while still maintaining good waveshape at all frequencies, range switching of the conversion resistor is recommended.

Suppose for an example that the desired frequency range is 16 Hz to 16.4 KHz (10 octaves). The upper 5 octaves could be served by a 20K conversion resister, requiring a Ct = 1.5 nF.

For the lower 5 octaves the highest frequency would be 512 Hz, requiring a conversion resistor equal to 640K. For both ranges, the lowest waveform control voltage necessary would then be 39 mV.

The range switching is most easily accomplished with the larger value resistor always connected to ground, and shorting a smaller value resistor to ground with a NPN or N channel MOS transistor to select the higher frequency range (Open collector or drain gates may be used for this purpose). In the above case, the smaller resistor would be 20.65K so that the parallel combination of the two resistors is the desired 20K.

Pulse Width Comparator

The variable width pulse waveform is generated by comparing the sawtooth developed across the capacitor Ct with the pulse width control voltage Vpw. The pulse duty cycle is therefore Vpw/Vp, or put in terms of the other variables, is:

$$\text{duty cycle} = \frac{Vpw}{5/12\ Vcc * \alpha} \times 100\% = \frac{Vpw * f * Rt * Ct}{Vwf} \times 100\%$$

As can be seen, the duty cycle is also affected by the particular waveshape selected for the sloped waveform (α fixed). Therefore, to keep the duty cycle (pulse width) constant as the waveshape is changed with the waveform control voltage Vwf, the pulse width control voltage Vpw must also be changed in direct proportion.

For example to generate a 50% duty cycle pulse with Vcc = +12.0V will required a pulse width control voltage equal to +1.25V when sawtooth is selected (α =1/2), +2.5V when a perfect triangle is selected (α =1), and +5.0V when a 50% clipped triangle is being outputted (α =2).

Waveform Selection

The sloped waveforms and pulse waveforms from each converter may be independently selected and mixed together by using the waveform select control voltage and pulse width control voltages. The waveform select control voltage is a four-level control which allows the sloped waveforms to be selected (on) or not selected (off). From -5V to -1.5V, both the sloped waveforms from converter A and from converter B are "on"; from -1.5V to +0.5V, the sloped waveform from converter A turns "off" while that from B remains "on"; from +0.5V to +2V, the sloped waveforms from both converters are "off"; and from +2V to +5V, the sloped waveform from converter A is now "on" while that from converter B remains "off".

Since the waveform select input is also a high impedance input, the necessary voltages may be generated in the same manner as the other control voltages -- multiplexed onto a hold capacitor from the system DAC. Another method for deriving the four select

voltages is simply to use two logic level outputs which drive the resistor-transistor network shown in Figure 2. For this method to work properly, the two digital outputs should swing from near zero to at least +4.5 volts.

The pulse waveforms from each converter may be turned "off" simply by setting the duty cycle (pulse width) to 0% with Vpw, and may be turned "on" by setting the duty cycle to anything greater than 0%. To ensure that the pulse is completely "off", it is recommended that Vpw be set slighty negative (e.g. -50 to -500 mV.

Trimming the Waveform Converters

As can be seen from the equation for waveshape control voltage Vwf, the value of Vwf required to produce a particular waveform (α fixed) is a function also of the conversion resistance Rt and timing capacitor Ct. Since these two components have tolerance (typically 1% or 5% for Rt and 5% or 10% for Ct), the required Vwf will also have a tolerance. In addition, there is an internal conversion error not shown in the equation of $\pm$5% ($\pm$15% worst case). The result is that with the theoretical Vwf required to generate a particular waveform, that waveform could have a 20% or more error in waveshape. For a sawtooth or clipped triangle, such an error is only mildly discernable; but for a triangle waveform, errors in excess of 5% can be easily heard.

If lower error in the waveshape is required, there are two possible methods for trimming. In both methods, the trimming needs only to be done at one point since the V/I converter is very linear and has low offset. The recommended point is at a Vwf between 0.2V and 1V.

The first method is simply to trim the conversion resistance for the proper waveshape (triangle is easiest) at a given Vwf and frequency. Then all other waveshapes at other frequencies will follow the theoretical values for Vwf. Besides requiring manual trimming, this method becomes impractical when range switching of Rt is used.

The second method is to trim Vwf with software for the proper waveshape at a particular frequency. Then once the corrected Vwf is found for this one waveform and frequency, the waveshape voltages required for all other waveforms and frequencies are derived from this value simply through calculation.

The easiest method for automatic adjustment of Vwf utilizes the fact that when the pulse width control voltage Vpw is 5/12 Vcc, the pulse width will be 100% when the sloped waveform is a perfect triangle regardless of the values of Rt, Ct, or the internal conversion error of the V/I converter. Thus, the software adjusts Vwf at one particular frequency using successive

approximation techniques until the pulse output just begins to produce a very narrow pulse. The resulting error in the corresponding triangle wave will be typically less than 1%. The very narrow pulse can be detected simply with a set-reset flip-flop. Since the accuracy of this method is partially dependent on Vpw being exactly 5/12 Vcc, it is recommended that the Vcc and the reference for the DAC be derived from the same source, and that the full scale output of the DAC be trimmed to within 1% relative to Vcc. An added benefit of trimming the sloped waveforms in this manner is that the duty cycle of the pulse waveform will also be corrected.

Output VCAs

The inclusion of two VCAs in series at the output, one with linear control scale and the other with audio taper control scale, allow much greater flexibility and control over the output signal level than in the usual case of only one VCA. Since the final output is a current with a voltage compliance to within 1V of either supply, the outputs of multiple CEM 3396s may be mixed together simply by tying all the output pins(pin 23) together and converting to a voltage with a single op amp.

The maximum peak-to-peak voltage contribution from each 3396 is 4.Ø volts times the ratio of output conversion resistance (in the feedback loop of the op amp, for instance) to the AC resistance at the VCA Gain Set pin(pin 21). For best performance, an AC resistance of around 1ØK is recommended. (The resistor must be isolated with a capacitor in series to prevent large DC offsets from appearing at the output).

The DC voltage appearing at the Gain Set pin varies from nominally +2.6V when the pulse width is at Ø% to +1.3V when pulse width is 5Ø% to ØV when the pulse width is at 1ØØ%. Thus the polarized isolation capacitor must be connected with the negative end connected to ground.

In a typical application, one VCA is used for the envelope control of the output signal, where its control voltage is either generated by a hardware envelope generator (such as the CEM 3312 or CEM 3371) or totally in software by a microprocessor. The other VCA may be used for a variety of purposes, including keyboard dynamics, modulation effects (tremolo), and controlling the mix between channels in a multi-chip system. Although controlling the amplitude of the envelope control voltage can achieve theoretically the same results, the variation in the VCA "on" threshold of Ø - 15ØmV can severly distort the envelope at low levels. Thus use of two VCAs allows control over wider dynamic range, simpler software, and more amplitude control functions to be implemented within the chip.

The availability of a linear control scale on one VCA and an audio taper scale on the other VCA offers additional possibilities in the tailoring of the instruments characteristics. The audio

taper control scale is essentially exponential from -90 dB to -15 dB (correspondig to a control voltage from Ø to +3.3V) and linear from -15 dB to Ø dB (corresponding to a control voltage from +3.3V to +5V). If the envelope control voltage is generated already with an RC (exponential) shape, then the linear VCA is the best choice for envelope control, leaving the exponential VCA for the other functions. When the exponential VCA is controlled by the keyboard voltage corresponding to velocity or pressure, only small changes in these parameters are required to produce large dynamic changes in the volume. Another advantage of exponential VCA is when dynamics and modulation voltages are mixed together (normally in software), the modulation depth become smaller as the overall volume is lowered with the dynamics control.

On the other hand, the exponential VCA may also be used for the envelope control and the linear VCA used for the other effects. The advantage of this arrangement is simpler software for the envelope generation, where the slopes of the envelope control voltage may now be linear while still preserving the desired RC release characteristics of the sound.

External Signal Inputs

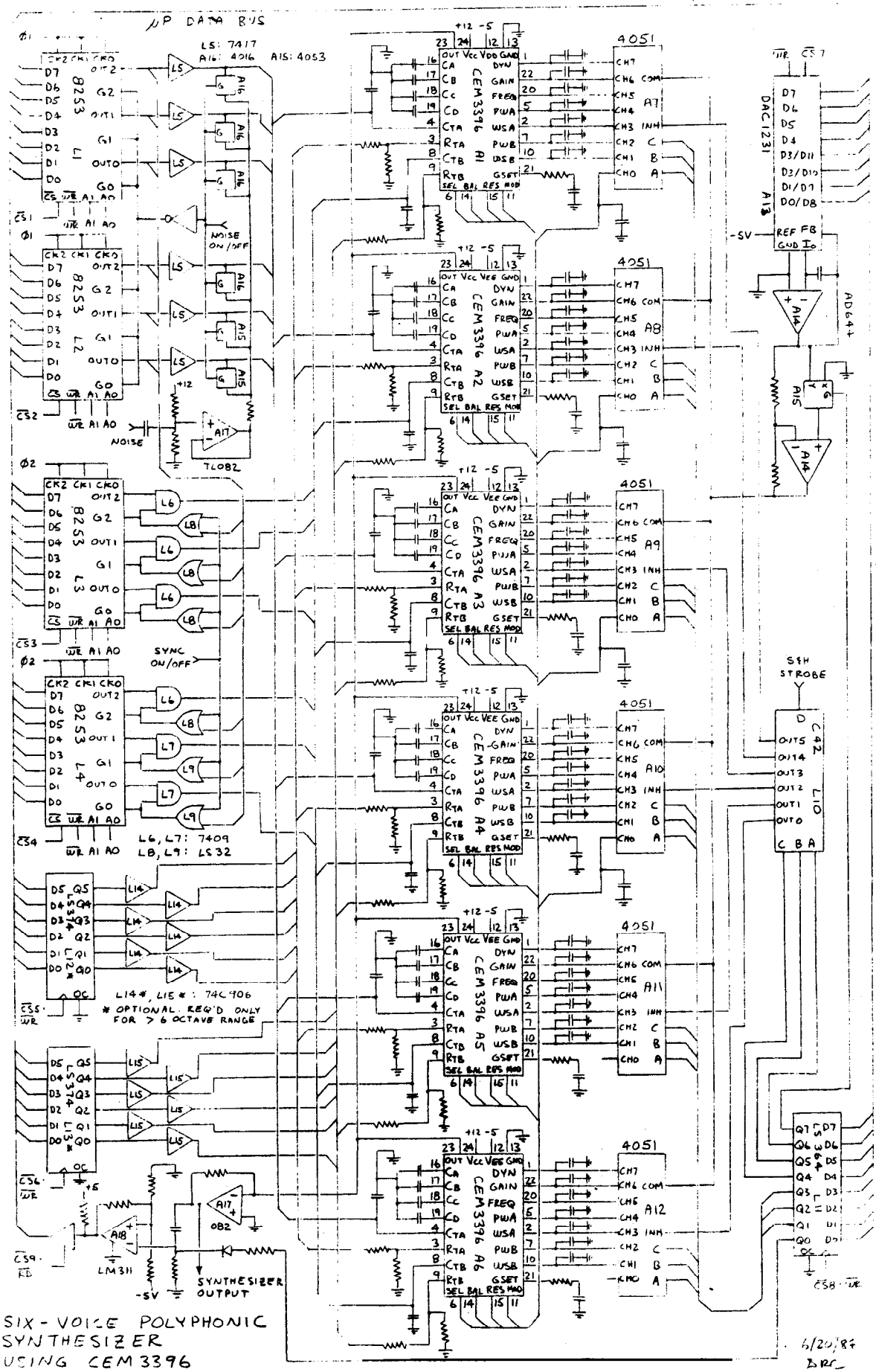
Although there is no specific pin for external inputs, external signals such as noise can be combined with the internally generated waveforms in several ways.

One method entails applying the external voltage to one of the waveform converter's capacitor (Ct) pin. Obviously during that time, that converter will not be able to generate its normal waveforms, but the Balance control will operate on the external signal. When applied in this manner, the external signal should have a DC average level of 5/48 Vcc and peak levels not less than ØV and not greater than 5/24 Vcc. The most straight-forward implementation of this approach is to connect with CMOS analog switches the output of an op amp biased at 5/48 Vcc to the capacitors of all waveform converters which are to receive the same external signal. At the same time, the discharge pulses to those converters must be inhibited. In general, the capacitors Ct will not limit the frequency response of the op amp below the audio bandwidth, but a small isolation resistance of several hundred ohms at the op amp output may be necessary to prevent oscillation due to the capacitive loading.

An alterntive method which requires no additioal analog switches is shown in Figure 1.

Another point to which an external signal may be applied is the first stage of the filter. The external signal is capacitively coupled to the Ca pin; the value of coupling capaciter should be Ø.Ø3 Ca divided by the amplitude of the external signal in volts peak-to-peak. This method allows both converters to generate their waveforms normally in addition to the external signal; the disadvantage is that the balance control does not affect the external signal, and the external signal receives only 3 poles of filtering rather than the normal 4.

Finally, if it is desired to apply the external signal after the filter but before the final VCAs, the VCA Gain Set pin may be used as the point of input. The external signal is simply applied to the end of the isolation capacitor which is normally connected to ground. The maximum voltage gain will be the ratio of the output conversion resistance to the capacitor series resistor. The external signal should be limited to about 2.5 V.P.P., and its source resistance should be much less than 6.8K, as can be obtained from the output of an op amp, for example.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L5: 7417
A16: 4016
A15: 4053
8253
L1
L2
L3
L4
NOISE ON/OFF
NOISE
TL082
SYNC ON/OFF
L6, L7: 7409
L8, L9: LS32
L14*, L15*: 74C906
* OPTIONAL. REQ'D ONLY FOR > 6 OCTAVE RANGE
LM311
-5V
SYNTHESIZER OUTPUT
CEM3396 A1
CEM3396 A2
CEM3396 A3
CEM3396 A4
CEM3396 A5
CEM3396 A6
4051
A7
A8
A9
A10
A11
A12
DAC1231
AD644
S&H STROBE
C42
L10
SIX-VOICE POLYPHONIC SYNTHESIZER USING CEM3396
6/20/84
BRS