Analog/Digital Guitar Synthesizer

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Project Definition

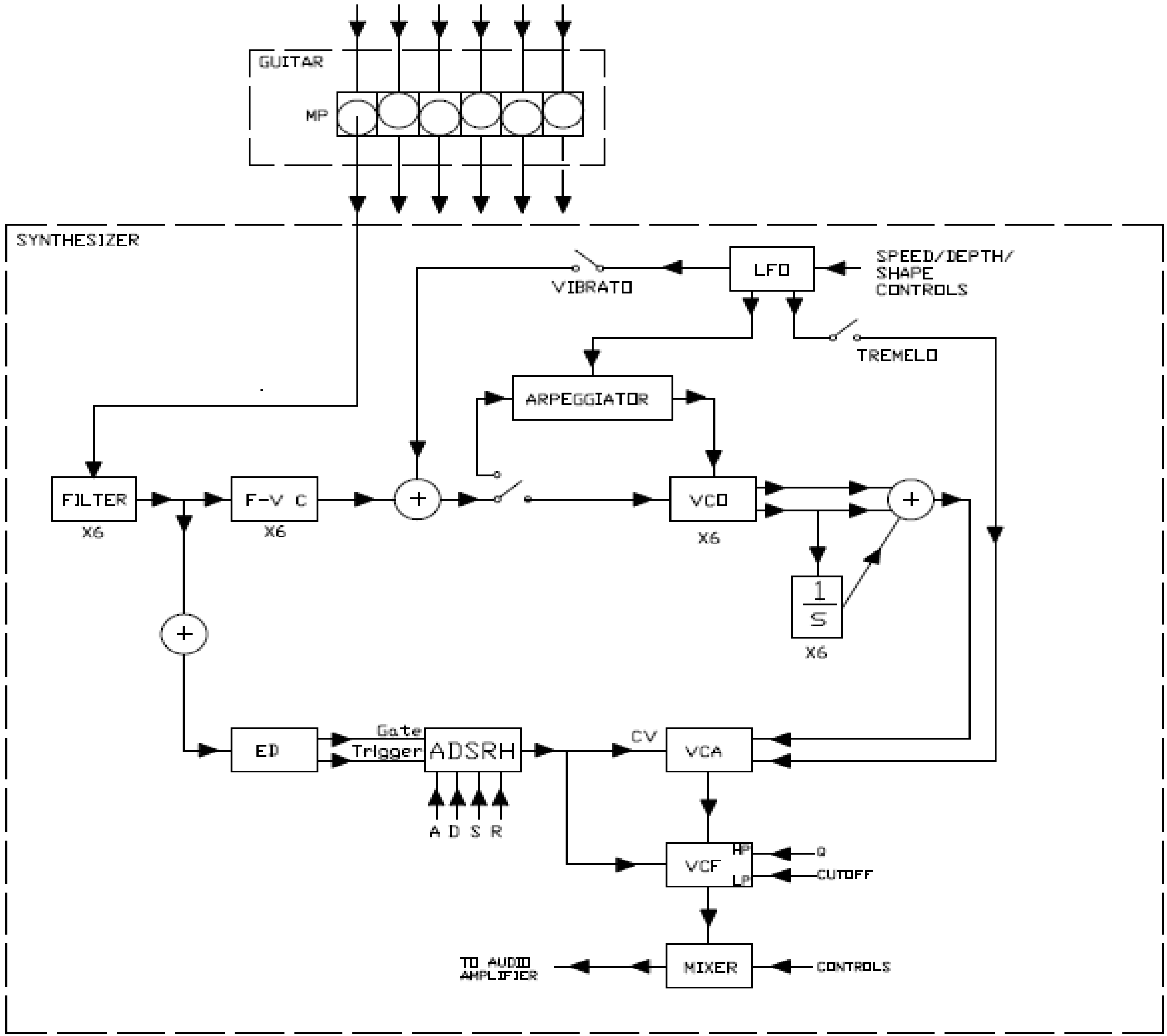
To use a guitar as a functional controller for an analog/digital synthesizer by taking information from a guitar as it's being played and create separate, fully controllable signals for each string.

Goals/Requirements

- Musicality
- Accuracy – must sound in tune
- Playability – real time, to be used as a live instrument
- Portability – a musician must be able to take it on the road and set up quickly
- Controllable – must give the user options to modulate/control the synthesized signals by on-board controls

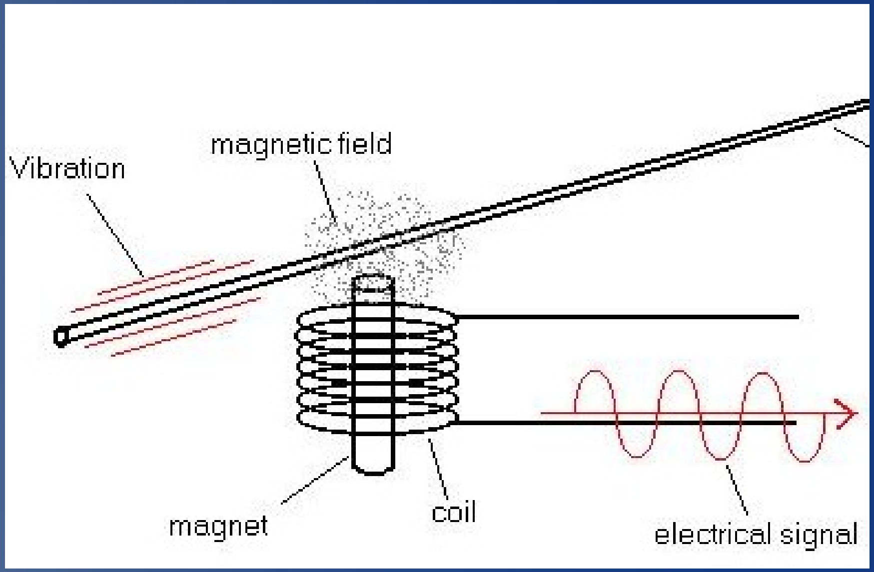
Specifications

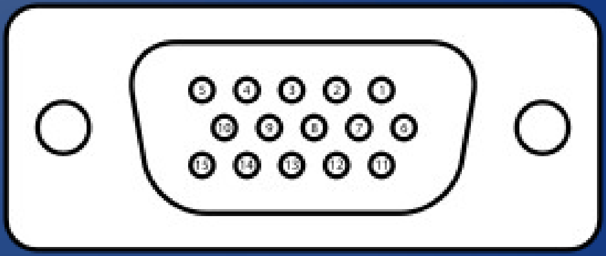
- Intonation – Within 3% of the note value's frequency
- Synthesize full frequency range of guitar – 82.4Hz to 1046.5Hz
- +/- 12V power supply
- Low Frequency oscillator with range from 3 to 33Hz
- <50ms delay from initial input to final synthesized note
- Microcontroller CPU speed 1MHz minimum


GUITAR
MP
SYNTHESIZER
LFO
SPEED/DEPTH/
SHAPE
CONTROLS
VIBRATO
TREMELO
ARPEGGIATOR
FILTER
X6
F-V C
X6
VCO
X6
1
S
X6
ED
Gate
Trigger
ADSRH
A D S R
CV
VCA
VCF
HP
LP
Q
CUTOFF
MIXER
CONTROLS
TO AUDIO
AMPLIFIER

Multichannel Magnetic Pickup

- Acquire the original envelope of the signal.
- Acquire the original frequency of the signal
- AlNiCo magnets are an industry standard.
- #30 g magnetic wire
- 6 individual signals must be produced.
- VGA cable has 15 pins.
- Problems can occur with a weak signal

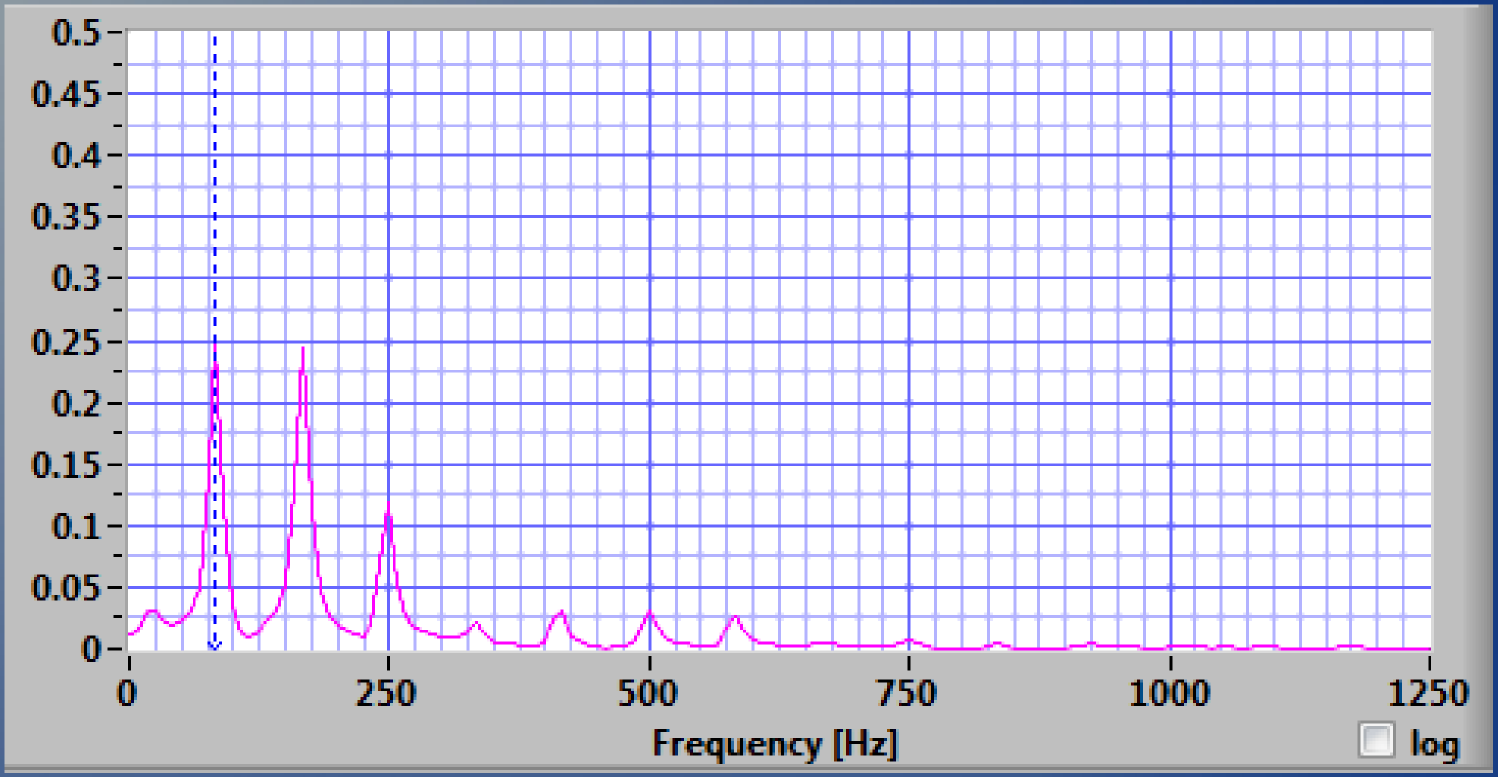




First Stage Filters

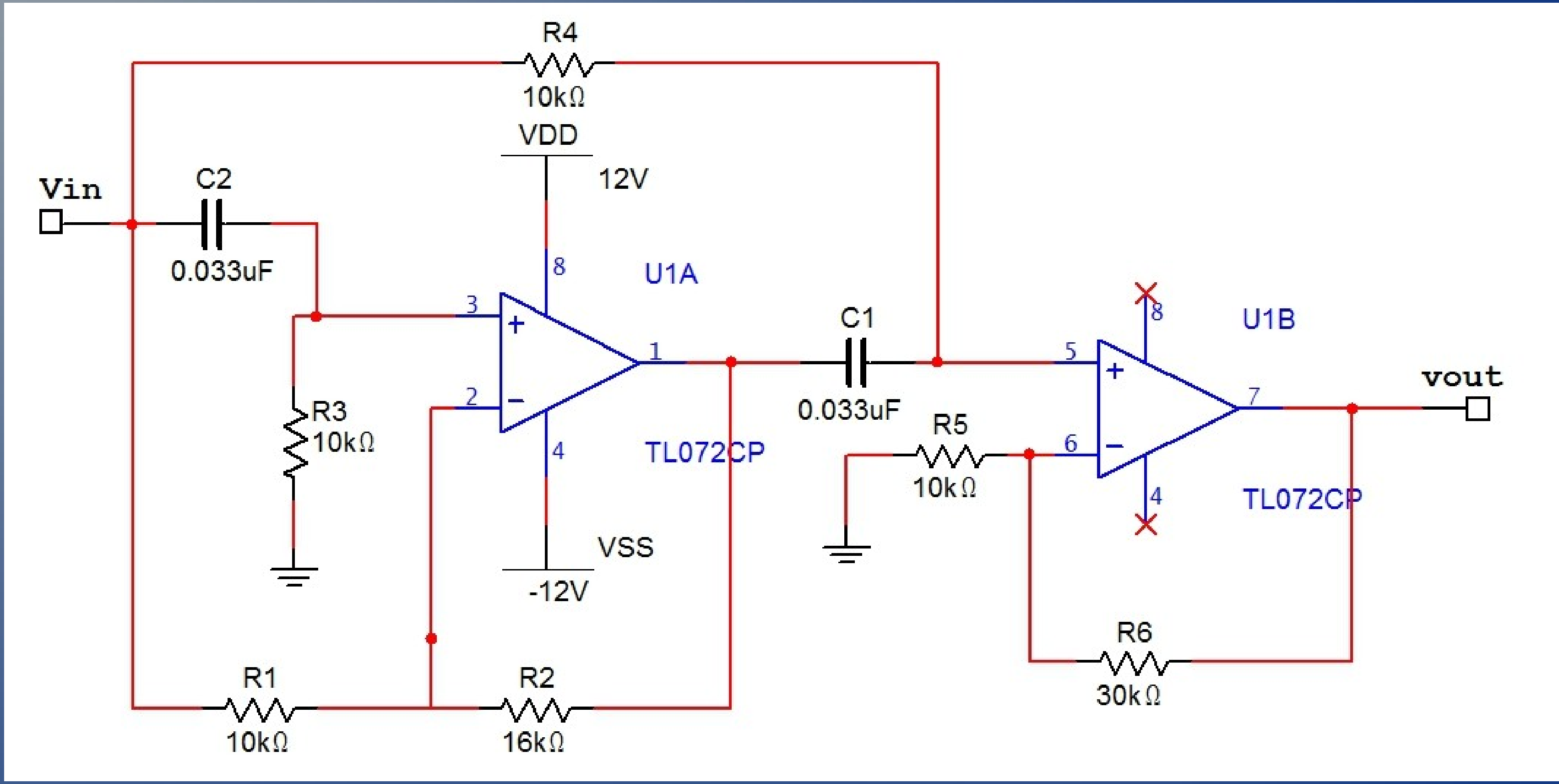
- Filter out naturally occurring harmonics from resonating guitar strings to allow for more accurate frequency tracking
- Must not completely filter out the 2nd harmonic, since this represents a valid note on the 12th fret (the octave)
- Must boost higher register on each string (shorter string, less energy = less volume and sustain for higher notes)
- Active notch filter centered at the 2^{nd} harmonic of the open note on each string

Spectrum of lowest note on the E string (82.4Hz)

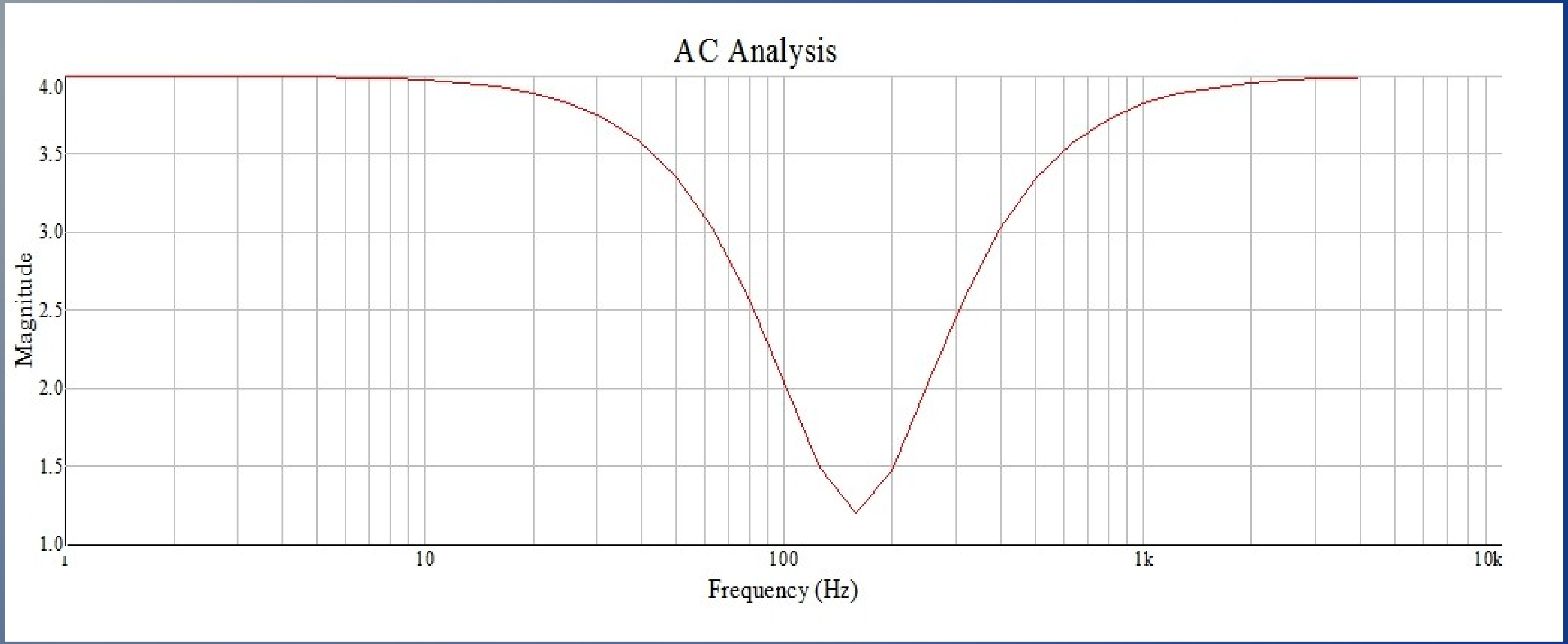


- Second harmonic is about as high as the fundamental
- Difficult to track frequency

Design



- First op amp is the notch filter, second stage is a gain stage of about 4
- Opamp are TL074 quad op amps to save space on PCB



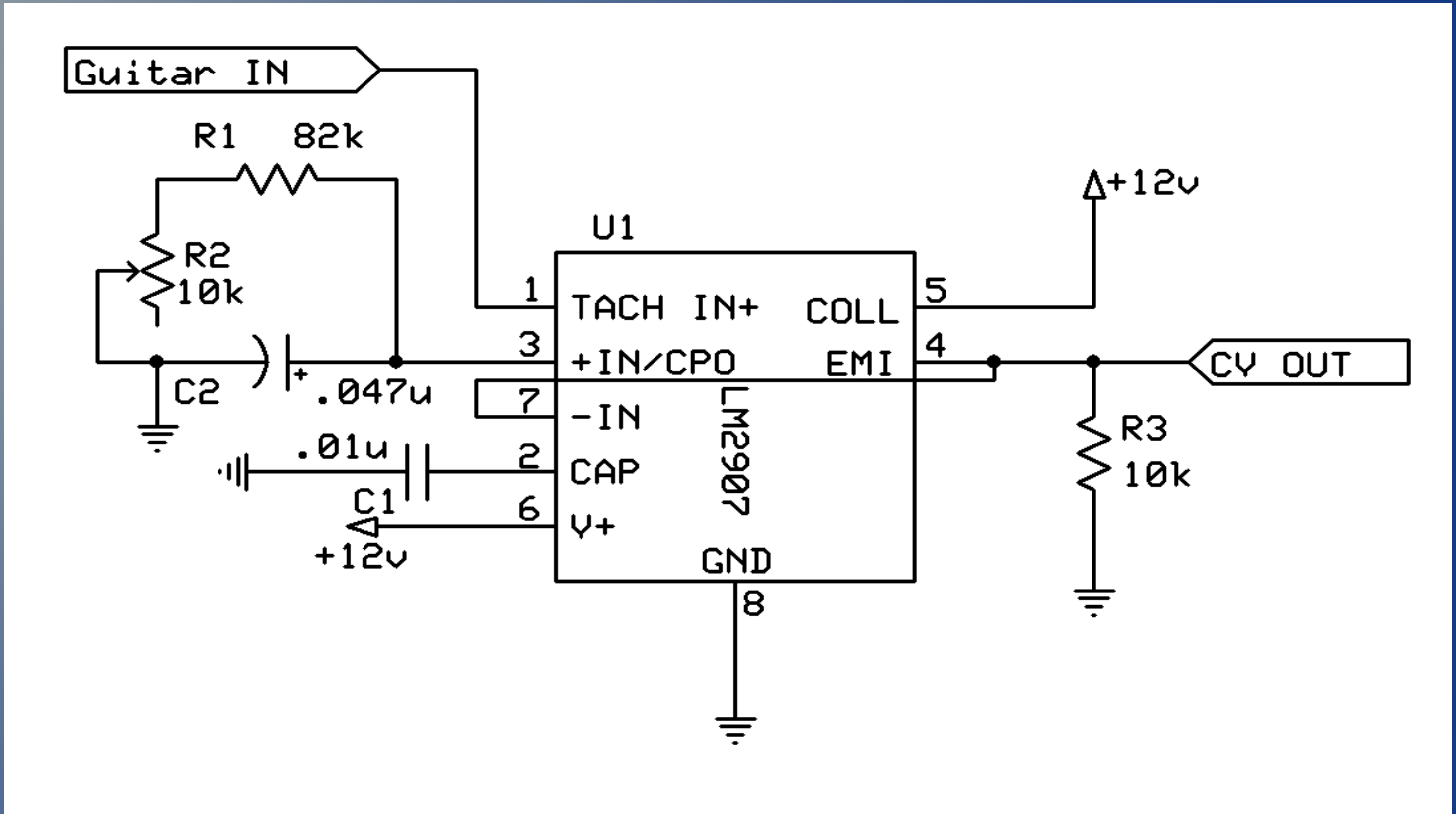
- Here: Low E string
- Gain of 2.5 for the lowest and highest notes on the string
- Gain of about 1.2 for the 12th fret. High enough gain for that particular note, but low enough in proportion to the lower fret's frequencies so that their second harmonics are overtaken by the fundamental.

Frequency to Voltage Converters
Requirements

- Linearly convert frequency of the individual guitar inputs to a voltage to be “read” by the VCO
- Must be accurate to within 3% of input (it must sound relatively "in tune")
- Each string will have a full range of 0 to 5V, designed up to the 20th fret

Design

- LM2907N frequency to voltage tachometer - 14pin dip
- Up to 28V supply range
- Designed specifically for variable reluctance magnetic pickups
- 0.3% linearity
- Easy design equation: Vout = Vcc * R1 * C1 * Fin,
- Useable range is about 1.6 to 5V from open to 20^{th} fret



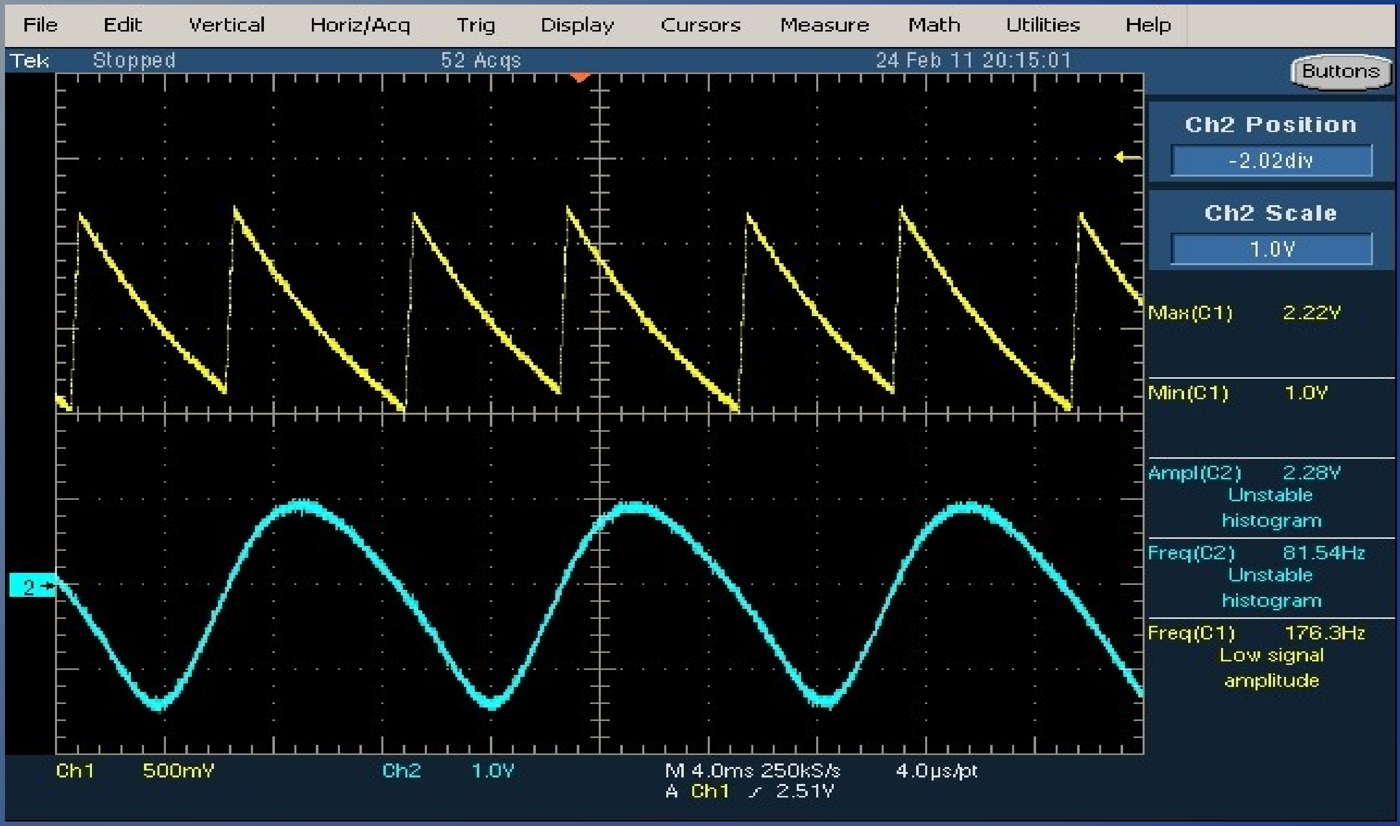
- C2 was selected to balance between quick response time and low ripple
- -the settling time is around 40ms. this might need to be shortened if the delay is too noticeable
- -even after "settling" there is still a ripple with twice the frequency of the input

Table of values for each string

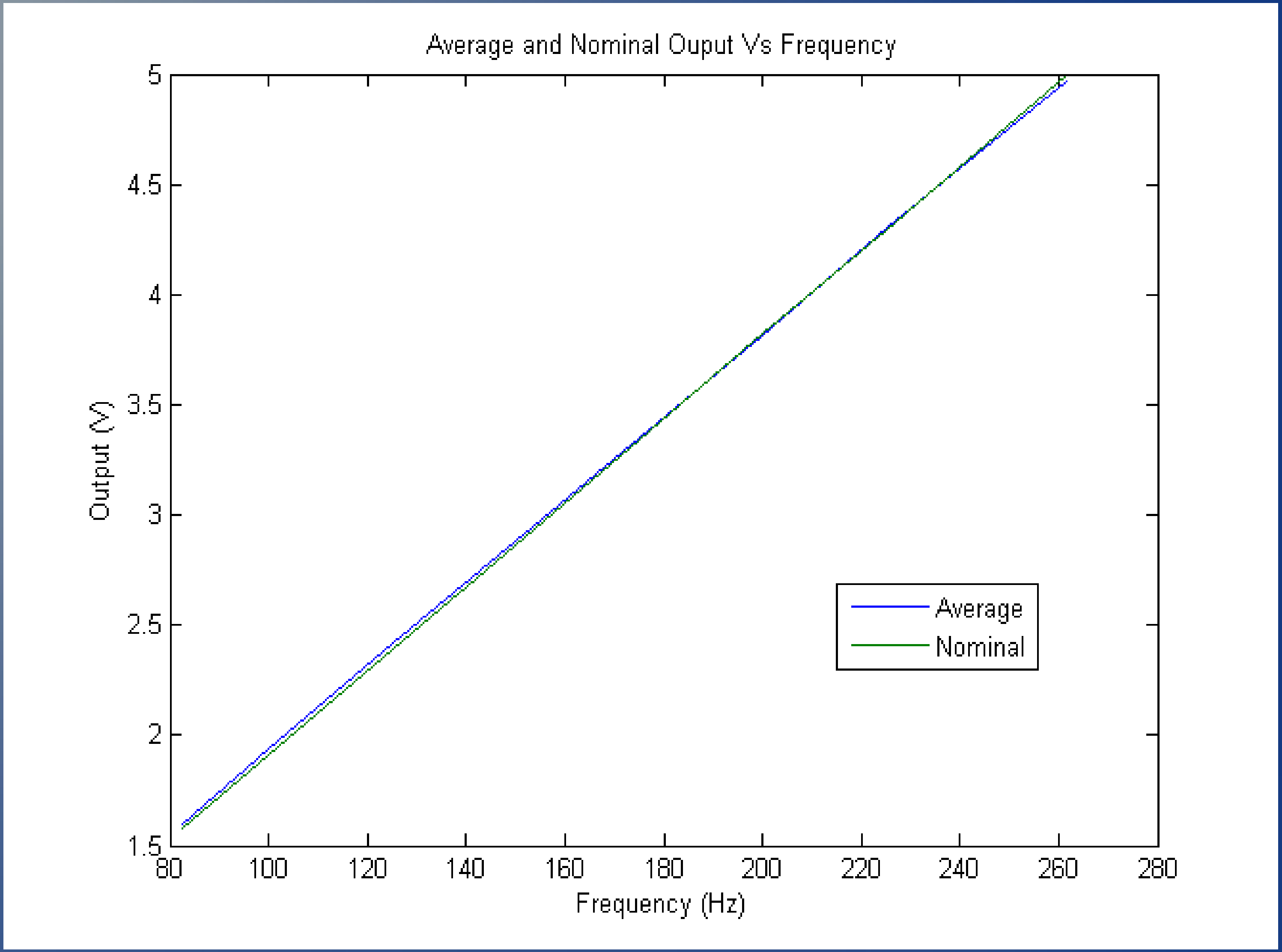
Open	20th fret	Slope	R desired	R + 100k trimpot	C
82.41	261.63	0.0191	160k	100k	0.01uF
110	349.23	0.0144	120k	82k	0.01uF
146.83	466.16	0.0107	160k	100k	0.0056uF
196	622.25	0.0080	120k	82k	0.0056uF
246.94	783.99	0.0064	240k	180k	0.0022uF
329.63	1046.5	0.0048	180k	120k	0.0022uF

- Real-world component values selected
- Trim pot will be used to "tune" the circuit during testing

FVC Signal From Pickup

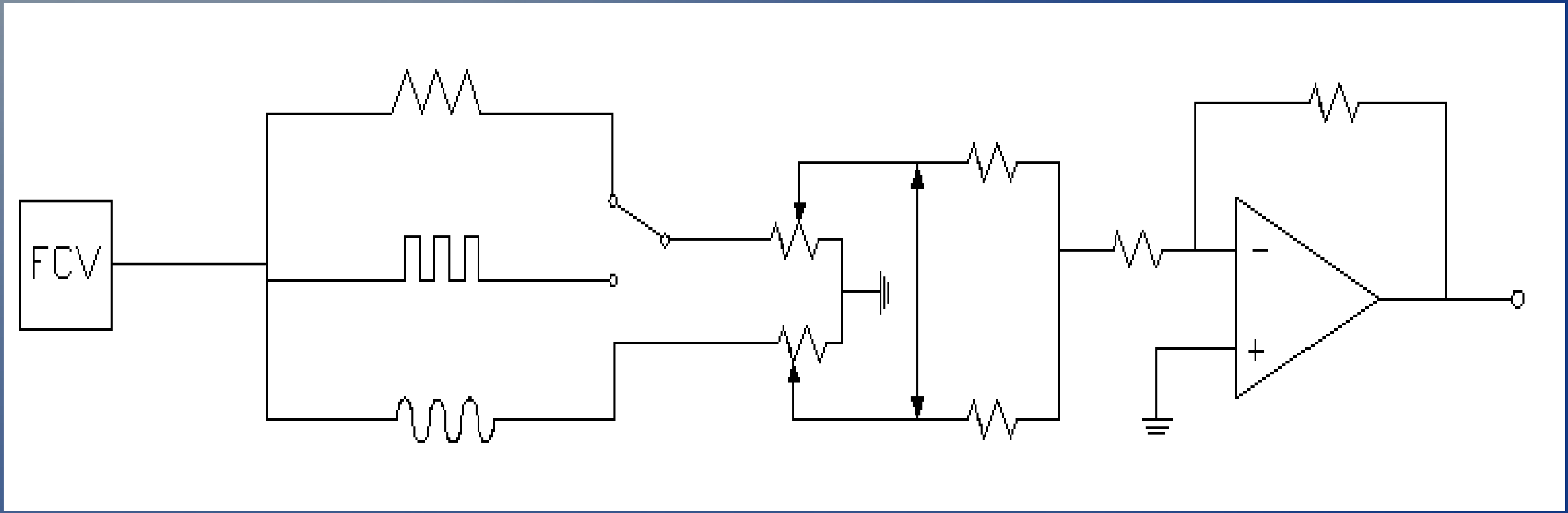


- Output ripple – would cause frequency variance problems of the VCO
- To be solved by the sample and hold block



- 1.65% error on the low end, 0.05% error on high end
- Sensitivity to error decreases as frequency increases
- Error on low end is more critical

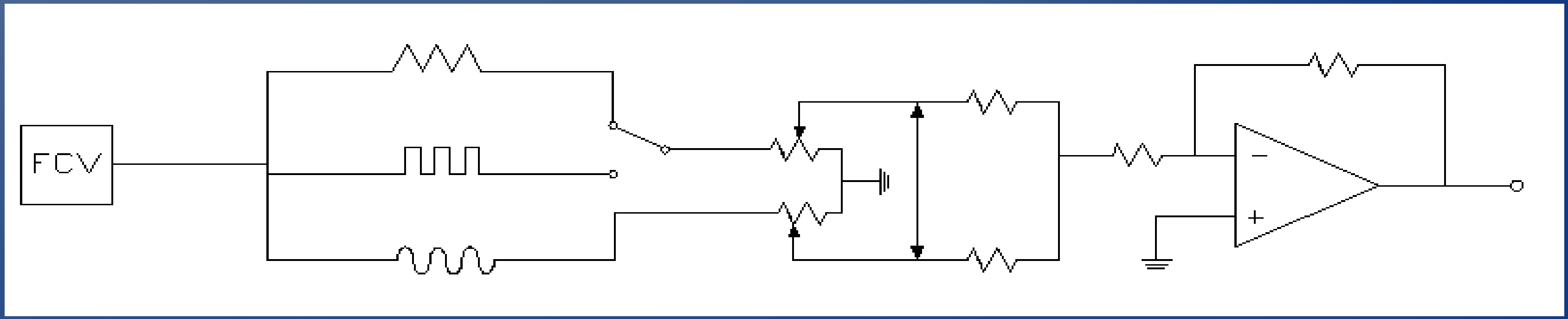
Overview



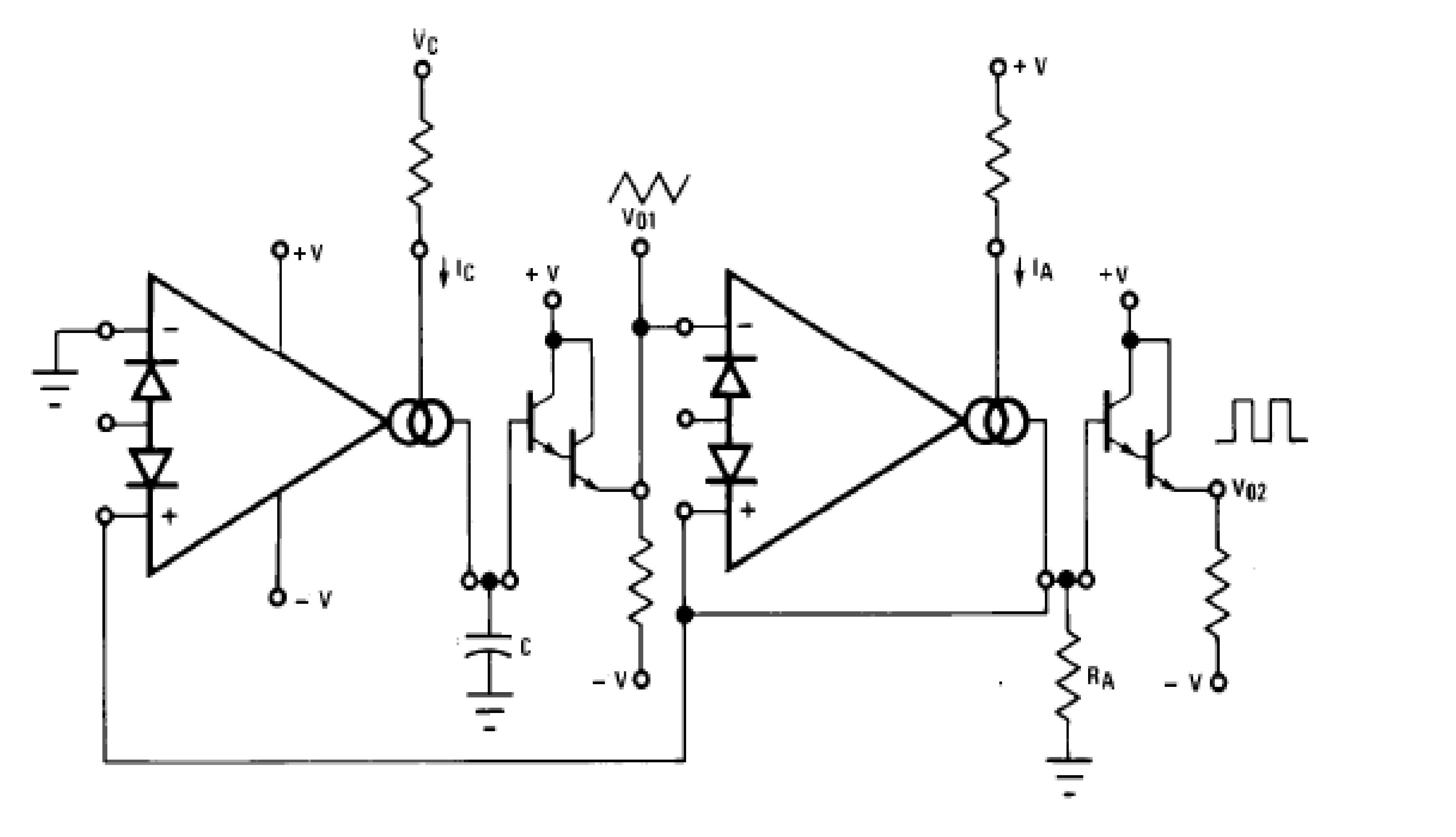
Wave Shaping Requirements

- Generate three waveforms of equal frequency, amplitude and peak-amplitude phase

  (Sine, Square, Triangle)
- Exclusively use analog components



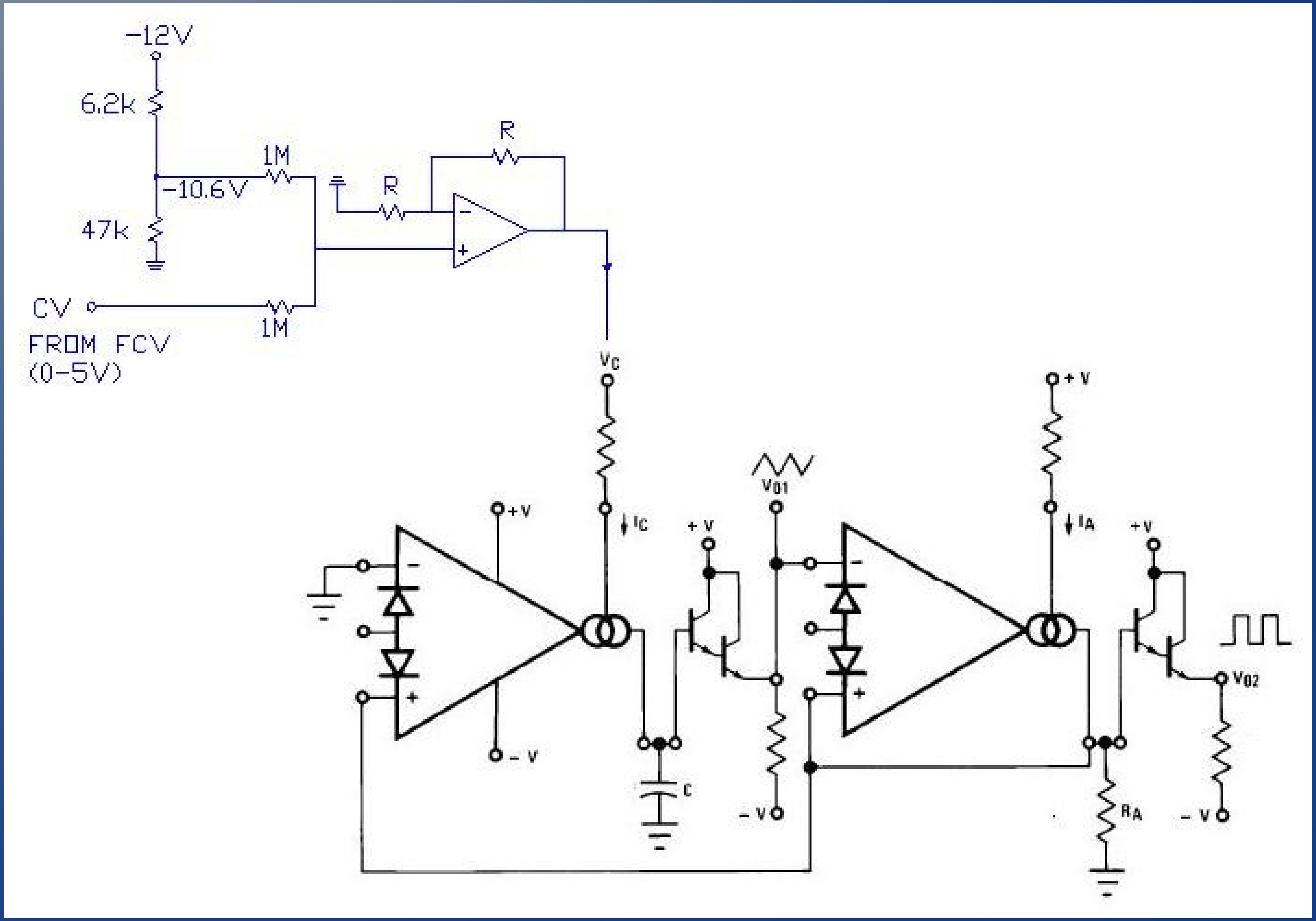
LM13700



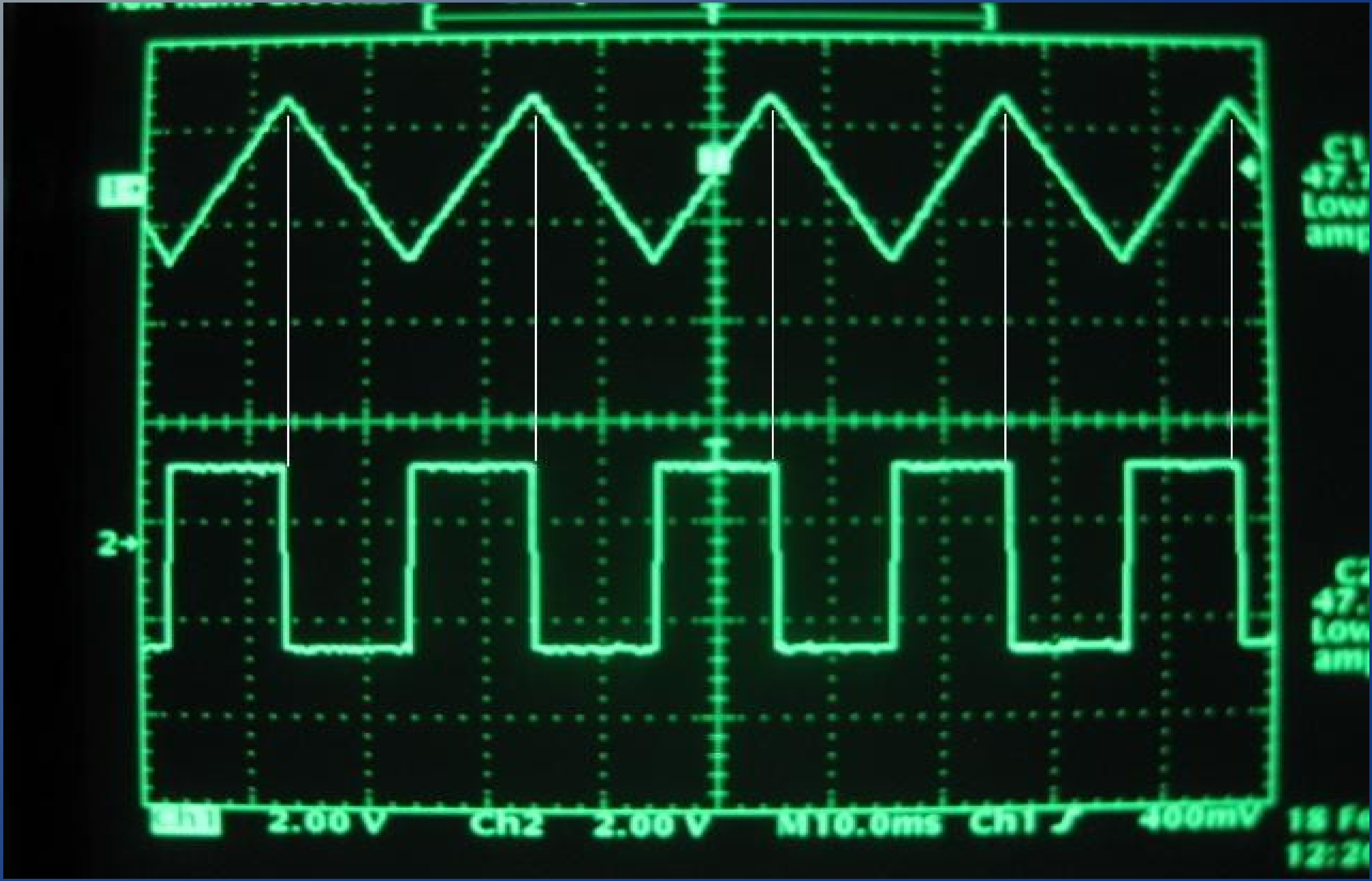
VCO Design Approach

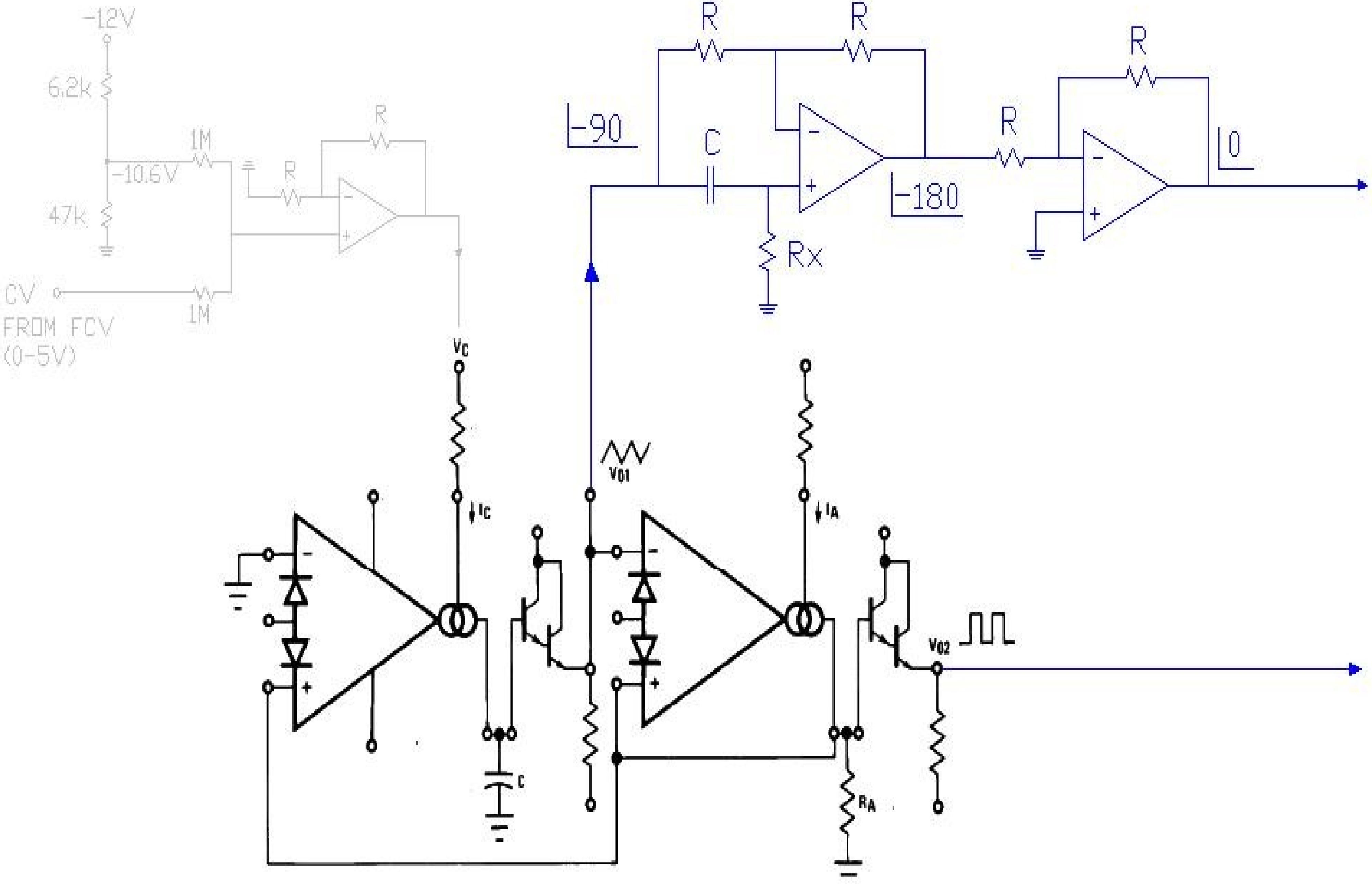
$$f_{OSC} = \frac{I_C}{4CI_AR_A}$$

$$I_C = \frac{Vc - 1.4 - V-}{R} \rightarrow I_C = \frac{Vc + 10.6}{R}$$



Testing & Problems

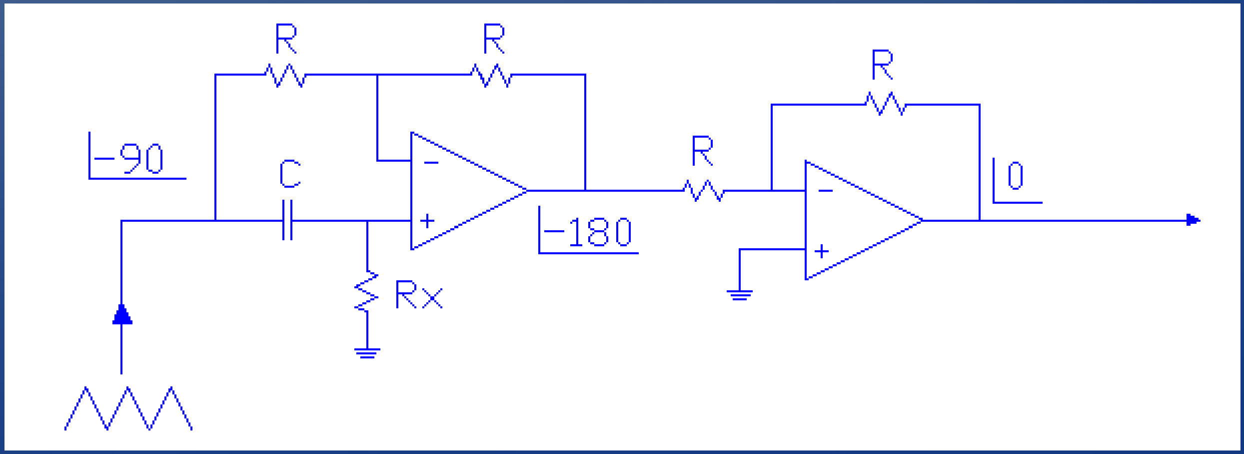




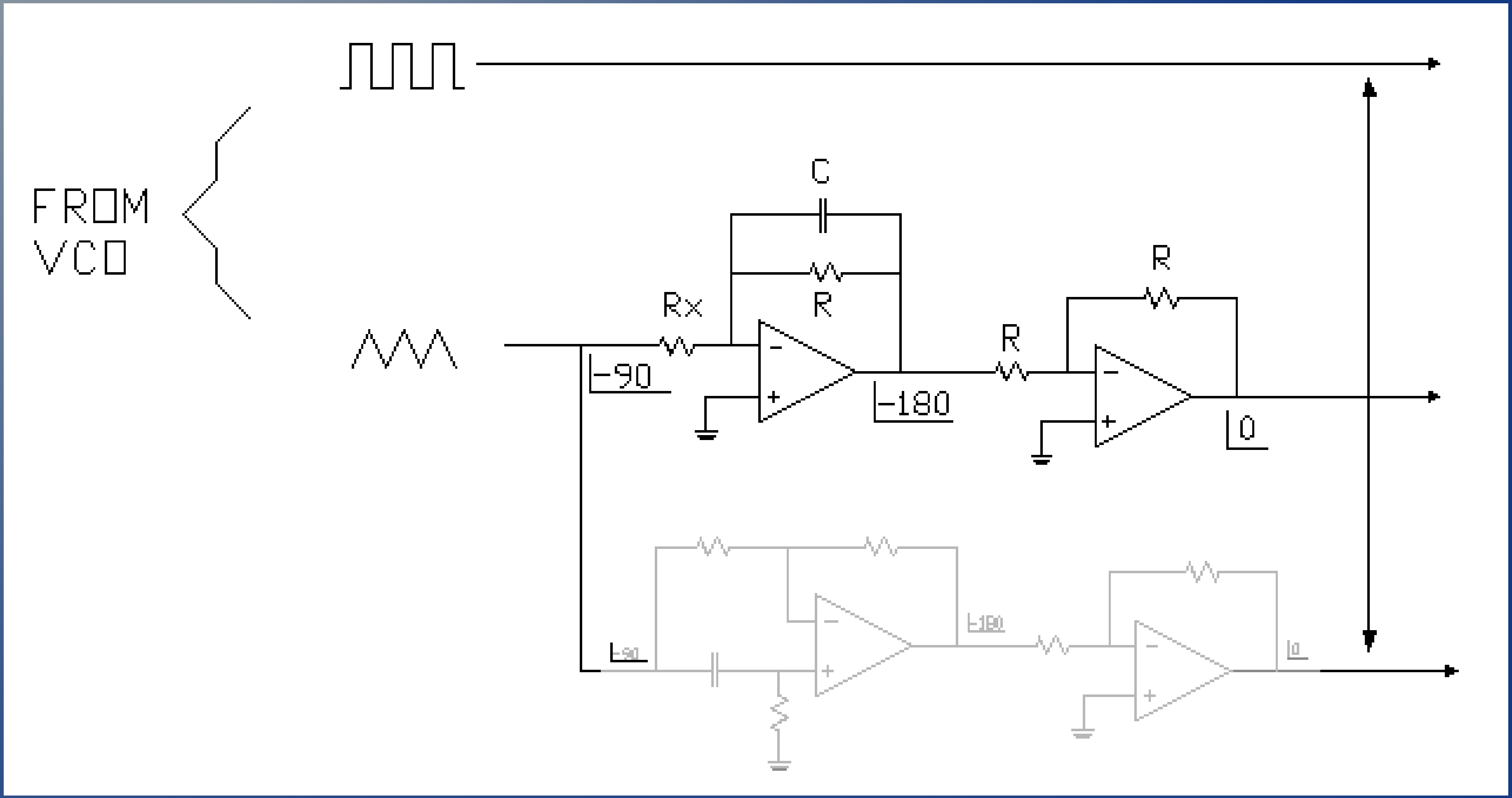
-12V
6.2k
-10.6V
1M
R
47k
CV
FROM FCV
(0-5V)
1M
R
R
-90
C
-180
Rx
R
R
0
Vc
Ic
V01
IA
V02
C
RA

All Pass Filter Design

- What to consider?
  - Phase variation at different frequencies
- w= 1/RC
- Use average frequency of each guitar string when choosing Rx and C
- Use equal values of R for both filter and inverter to maintain unity gain (and simplicity)

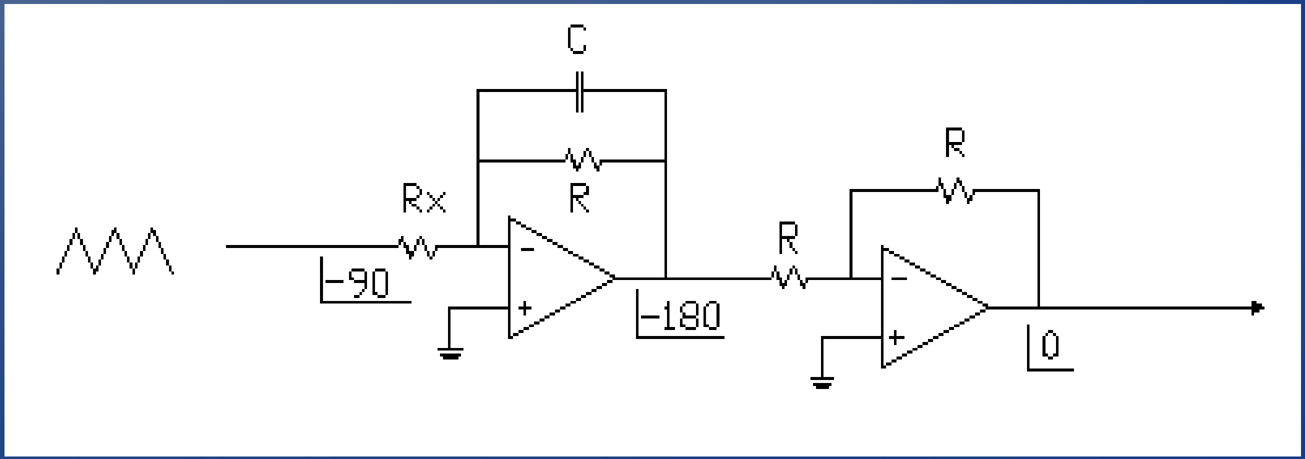


Sine Wave Generator



Integrator Design Approach

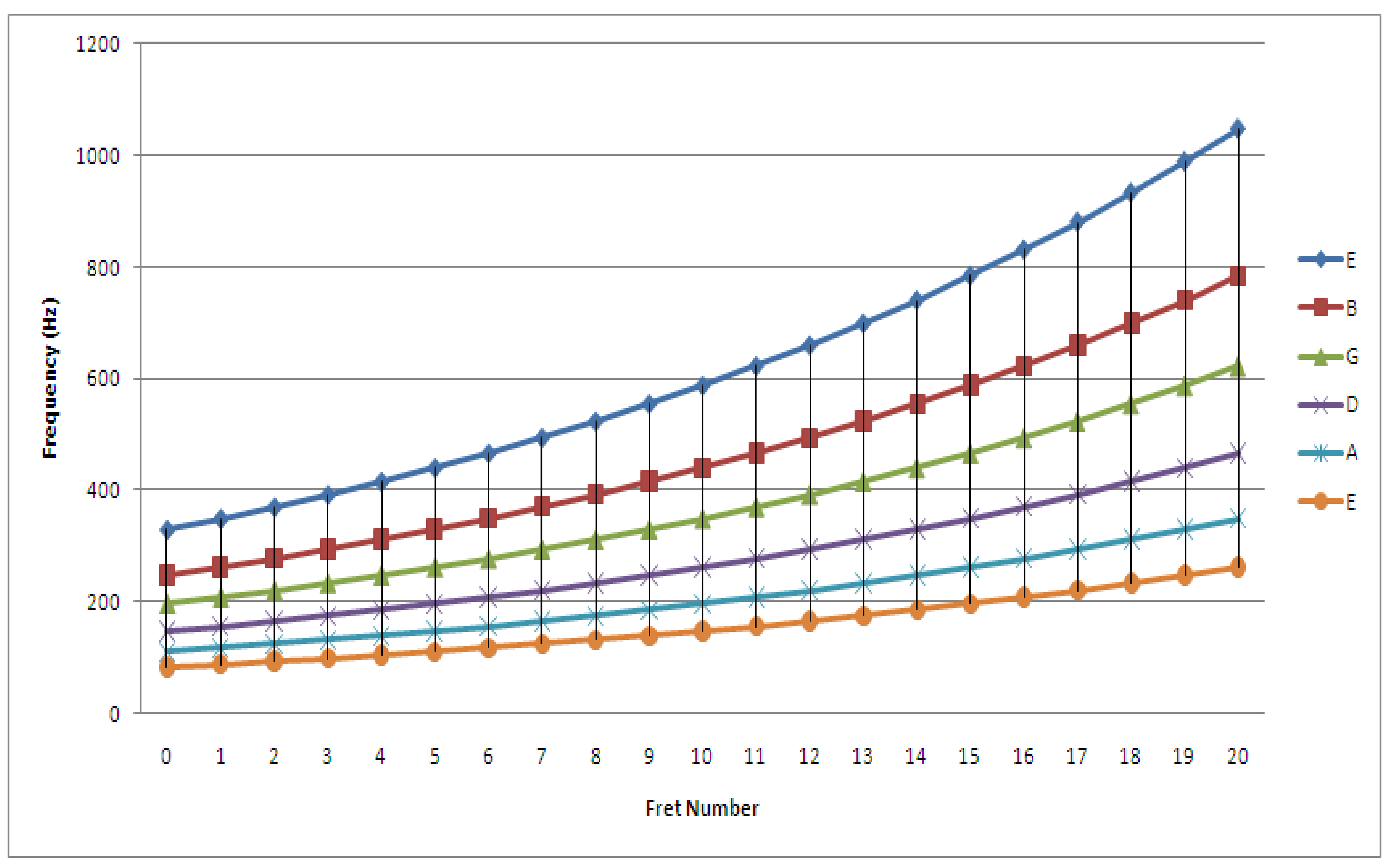
- Amplitude variation at different frequencies
- Design Rx and C based on average frequency
- w=1/RxC
- Match resistors R for unity gain



Parts Required

- Parts required
  - 1 LM13700 x6
  - 1 LF351N x 6
  - 2 Dual Op-amp x 6
  - 22 Resistors x6
  - 1 Capacitor x6

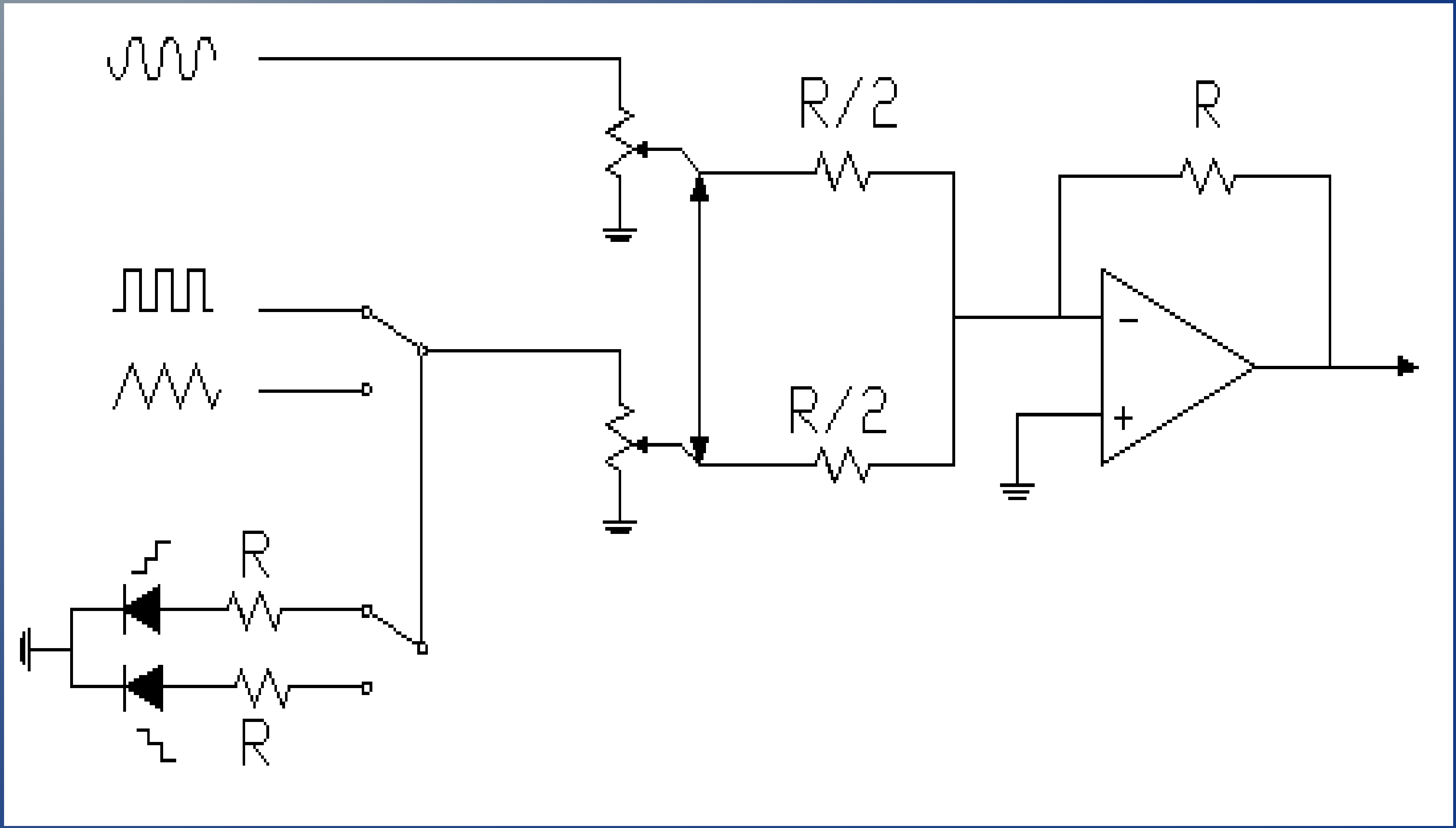
Improvements



Mixer Requirements

- Add two waveforms while maintaining unity gain
- Allow user to select between two waveforms to mix
  - Mix Triangle and Sine or
  - Mix Square and Sine
- LED's to indicate which waveform has been selected
- Allow proportion control between the two signals
- Mix all six resulting signals to send forward to filtering & modulation stages

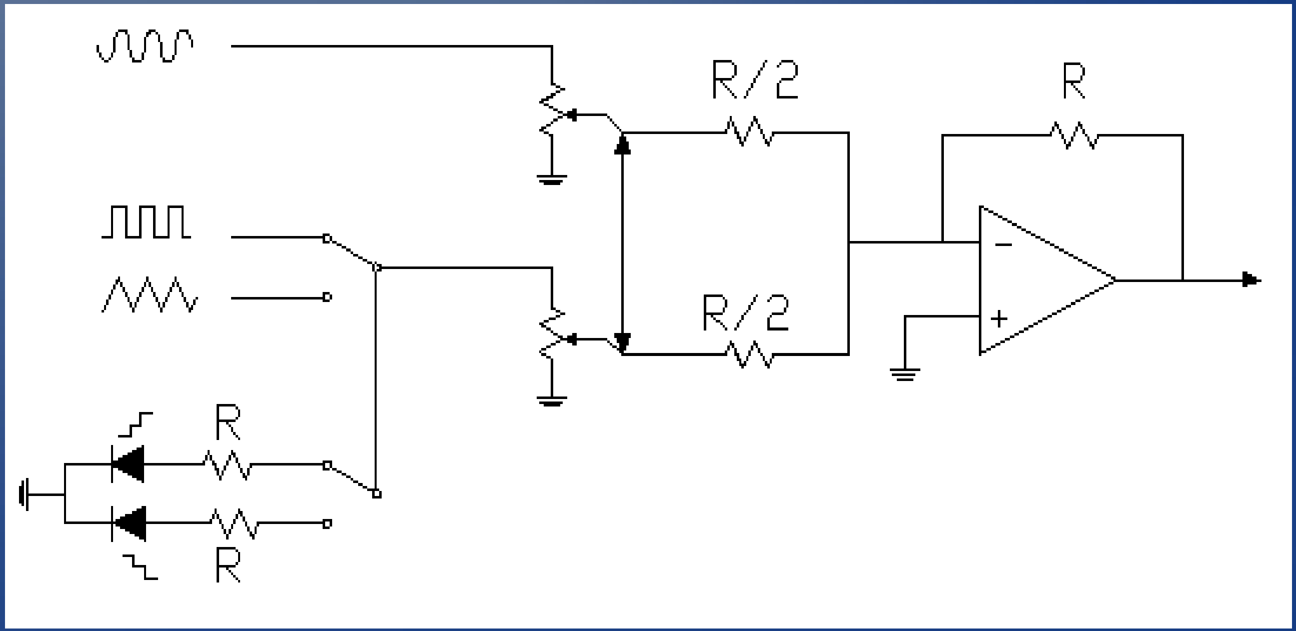
Independent Mixing Stage

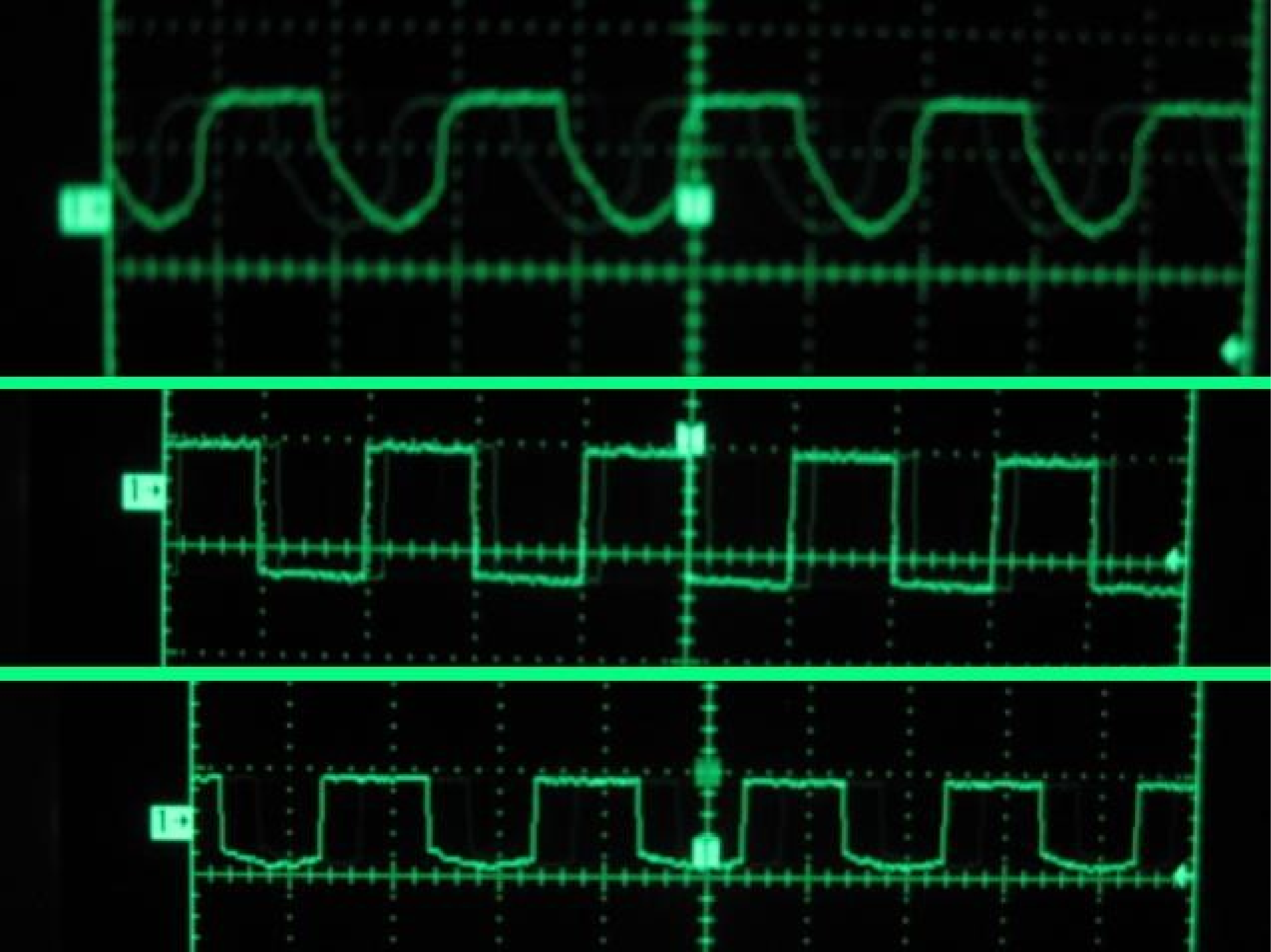


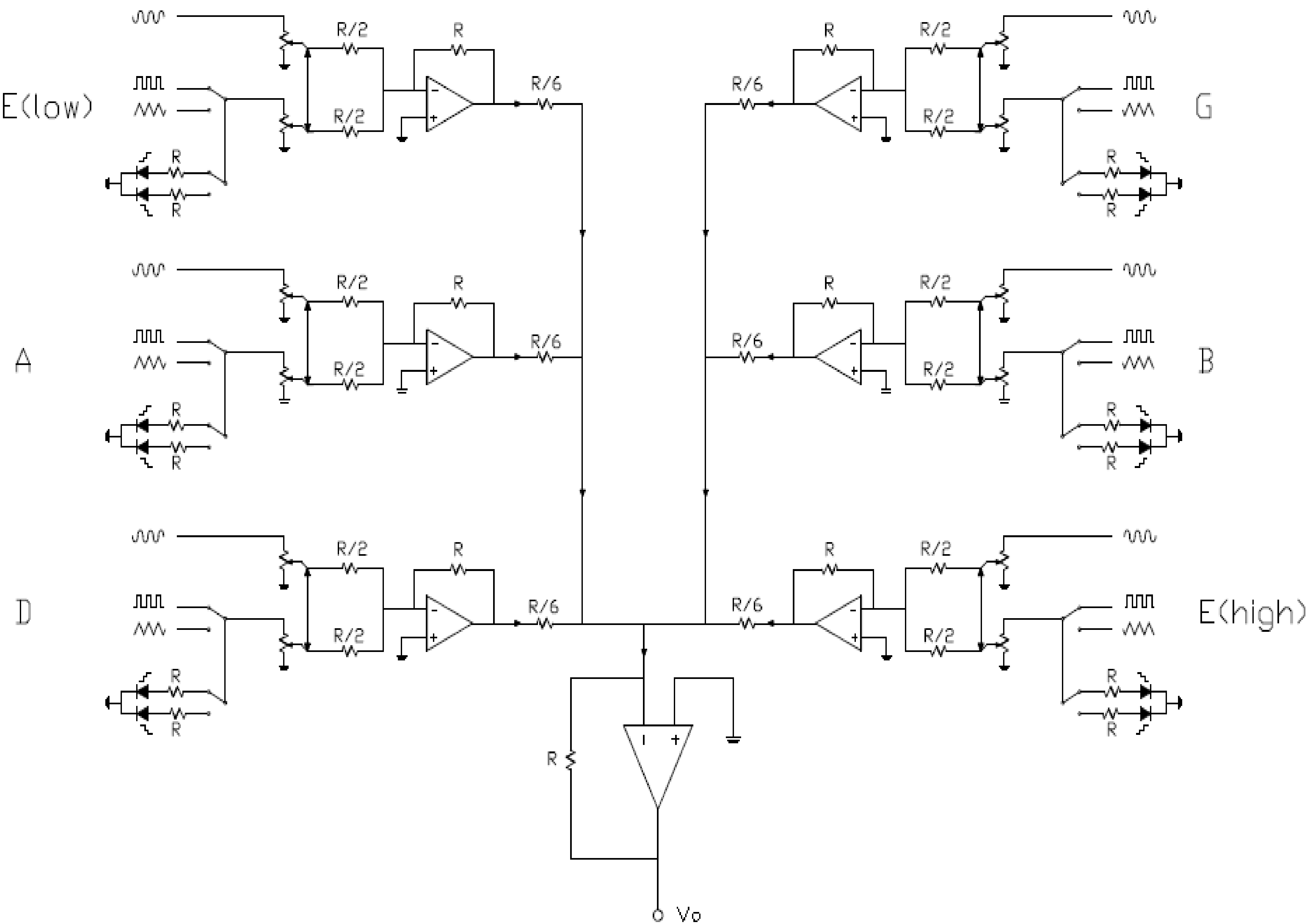
Design Considerations

- R values to achieve unity gain
- Dual-gang potentiometer for proportion control

~20% error is expected for sliding potentiometer







E(low)
A
D
G
B
E(high)
R/2
R
R/6
Vo

Parts Required

- 1 op-amp (LF351) x7
- 5 Resistors x6
- 2 LED's x6
- 1 DPDT Toggle Switch x6
- 2 Sliding Potentiometers x6

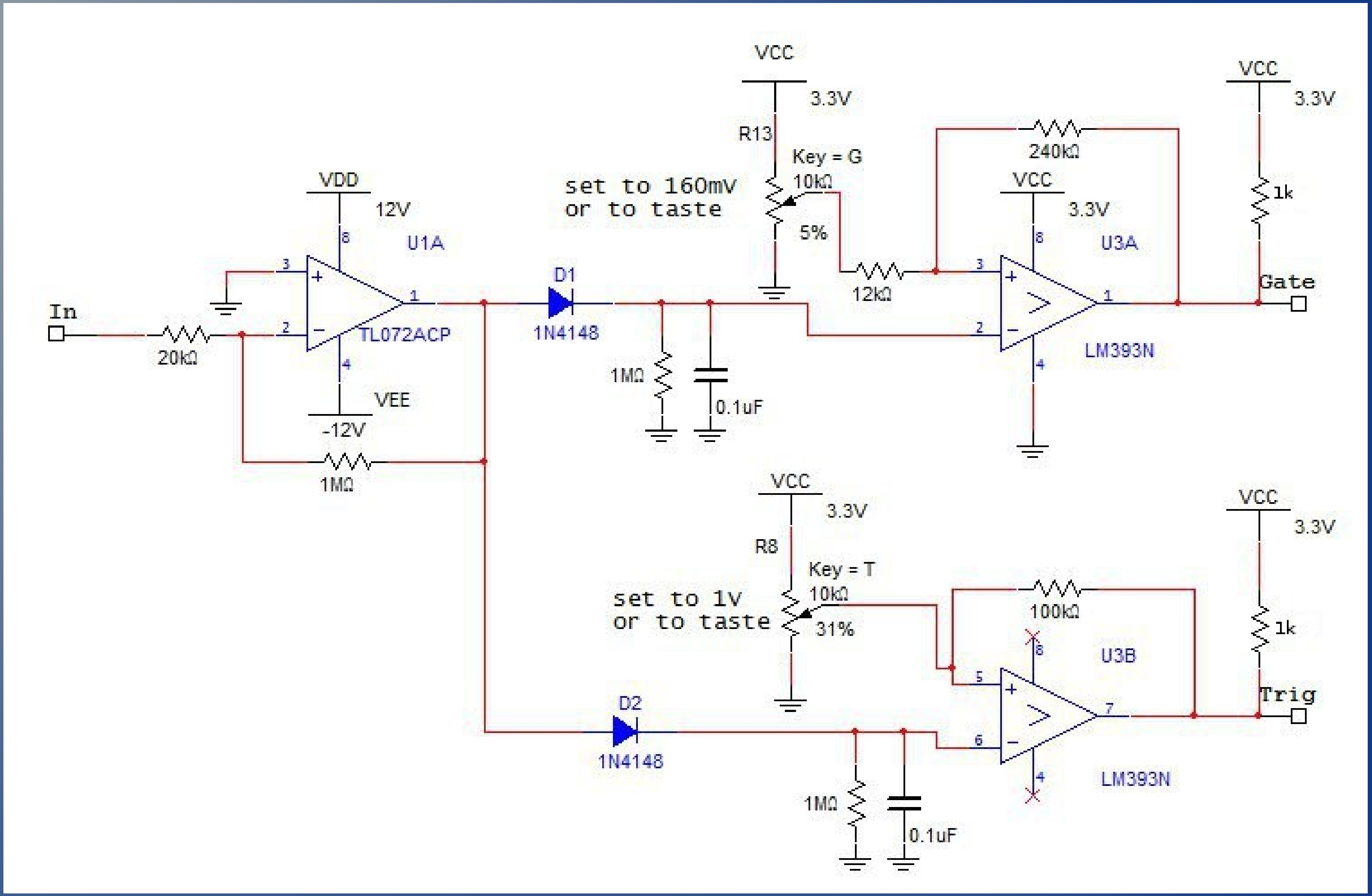
Triggers and Gates

Requirements

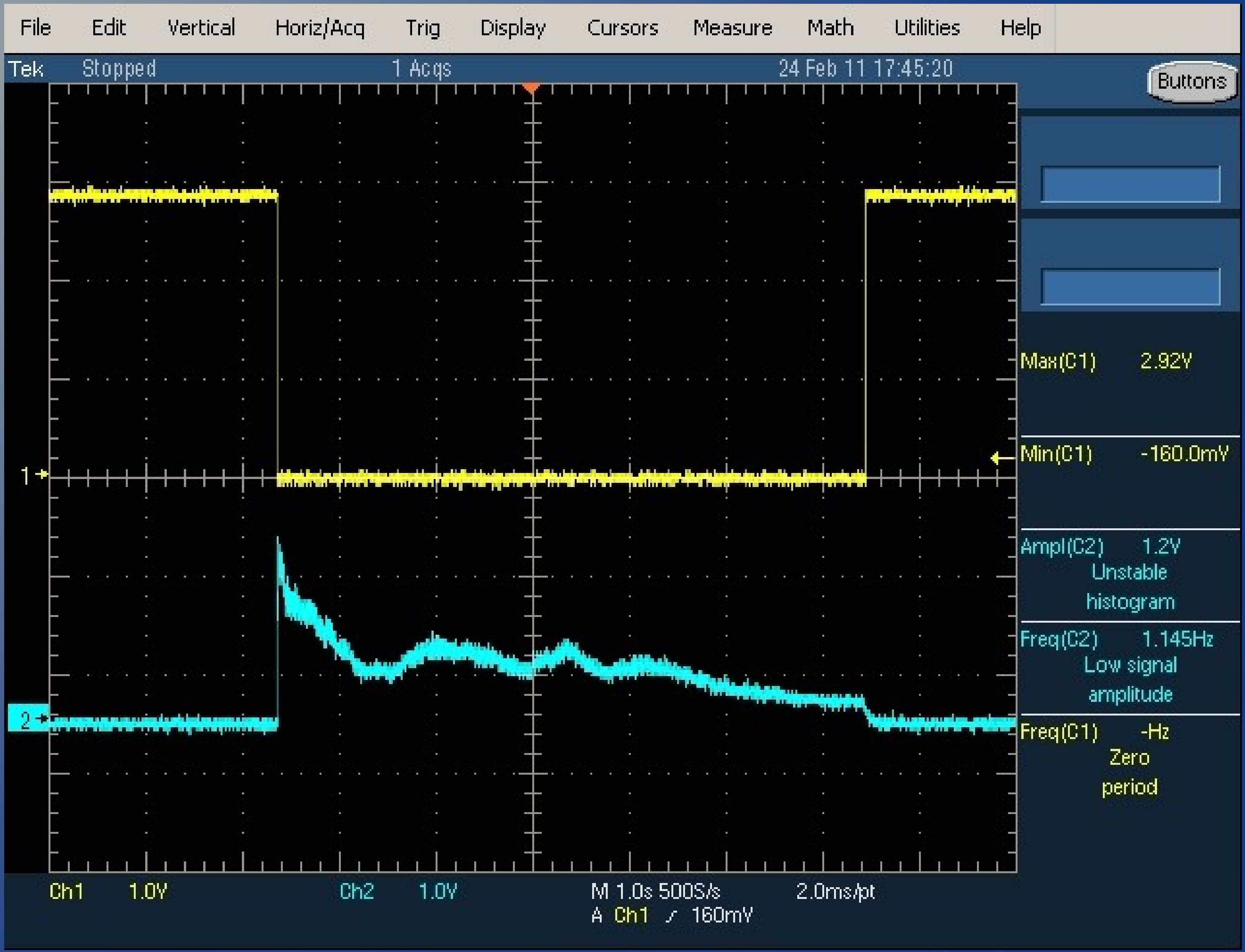
- The trigger is a binary pulse that is activated whenever a new note is hit on the guitar string
- Tells the sample/hold and ADSR blocks that a new note happened
- The gate is also a binary signal that is active whenever the pickups are sending signals
- Tells the sample/hold and ADSR blocks that a note is still being played

Design

- Simple envelope detector followed by two comparators - one for gate and one for trigger
- Inverting comparator using LM339 quad comparator
- Gate will have a voltage reference of about 150mV with hysteresis of about 100mV
- Trigger will be less sensitive, so that it is only high when a guitar string is plucked – about 1V vref
- The natural envelope of a plucked string falls sharply after the initial attack, causing the trigger to be a short pulse



- The trigger is similar to the gate, but with a higher voltage reference of about 1V
- The output will switch from 3.3V to 0V


File
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Trig
Display
Cursors
Measure
Math
Utilities
Help
Tek
Stopped
1 Acqs
24 Feb 11 17:45:20
Buttons
Max(C1) 2.92V
Min(C1) -160.0mV
Ampl(C2) 1.2V
Unstable
histogram
Freq(C2) 1.145Hz
Low signal
amplitude
Freq(C1) -Hz
Zero
period
Ch1 1.0V
Ch2 1.0V
M 1.0s 500S/s
2.0ms/pt
A Ch1 ⁄ 160mV


File Edit Vertical Horiz/Acq Trig Display Cursors Measure Math Utilities Help
Tek Stopped 1 Acqs 24 Feb 11 17:46:09
Buttons
Max(C1) 2.92V
Min(C1) -200.0mV
Ampl(C2) 2.44V Unstable histogram
Freq(C2) 2.039Hz Unstable histogram
Freq(C1) 2.049Hz
Ch1 1.0V
Ch2 1.0V
M 1.0s 500S/s 2.0ms/pt
A Ch1 ⁄ 160mV

Sample and Hold
Requirements

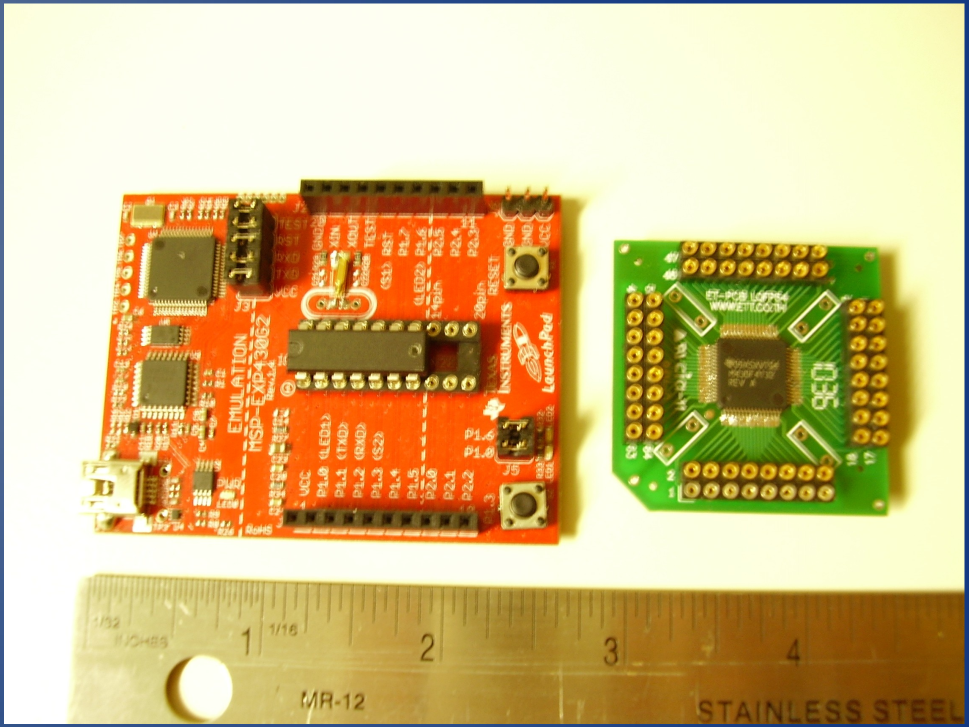
- Smooth out ripple from the frequency to voltage converter
- Samples the FVC signal, averages the values, outputs a smooth signal using a filtered PWM
- Allows the user to select between two modes - continuous and hold
- Continuous - continuously samples the FVC output while the gate is active
- Hold - activated via a foot switch, holds the last note(s) sampled. Allows some strings to be held while the rest are in continuous mode

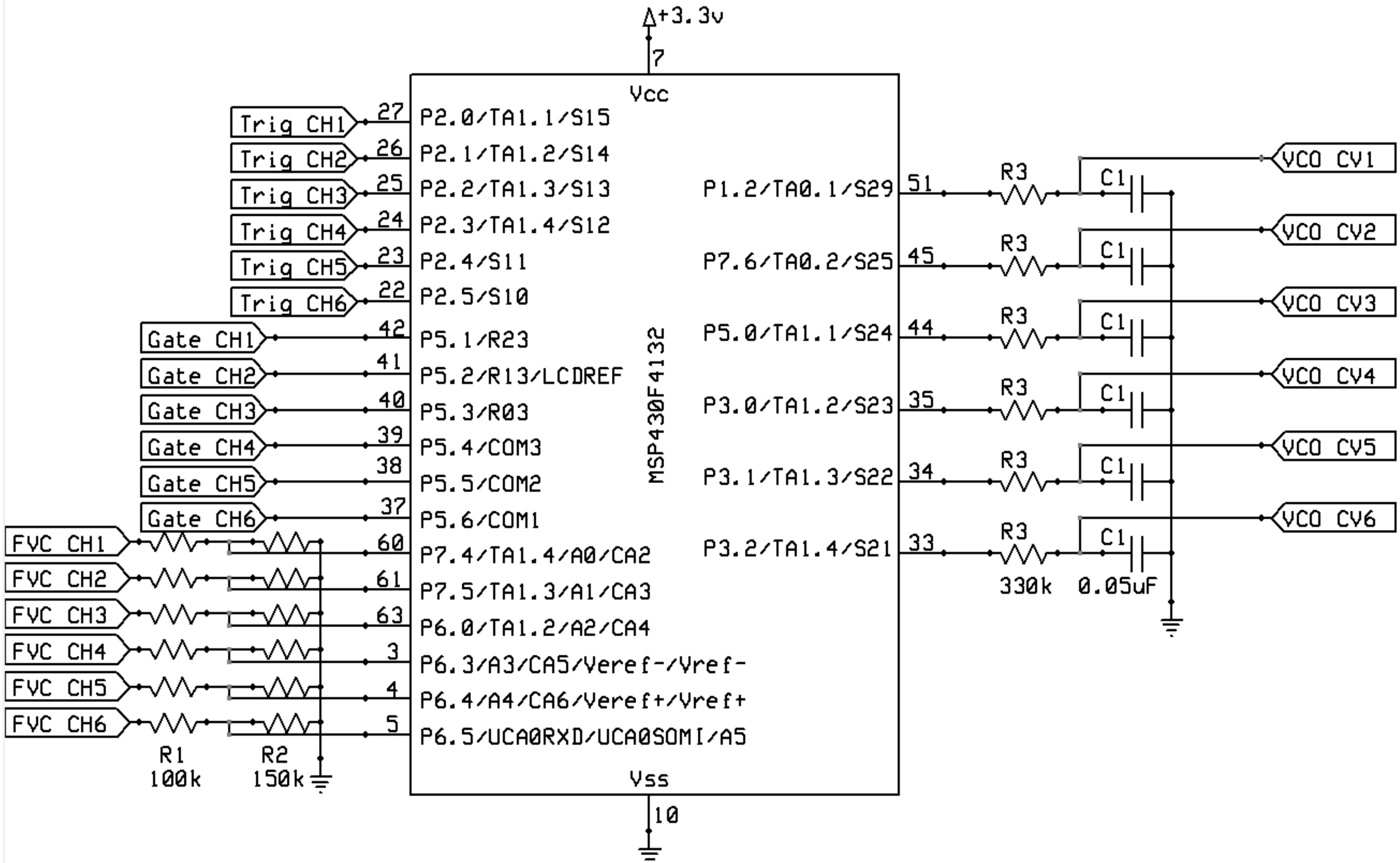
Microcontroller

- MSP430F4132 microcontroller
- 8KB Flash, 512B SRAM, 8MHz
- 56 GPIO, 64 pin LQFP package
- Has multiple port pin interrupts
- 8 10-bit ADC channels
- Outputs up to 6 PWM signals from capture/compare peripheral
- Will accept the trigger outputs as port pin interrupts
- Output will be filtered PWM signals sent to the VCO

MSP430 Development Board

- MSP430 Launchpad
- Cheap ($4.30), available, programmable in C using CCS compiler
- 64 pin breakout board for the MSP430F4132 (for testing only)
- Programmed by the Launchpad via Spy-bi-wire interface



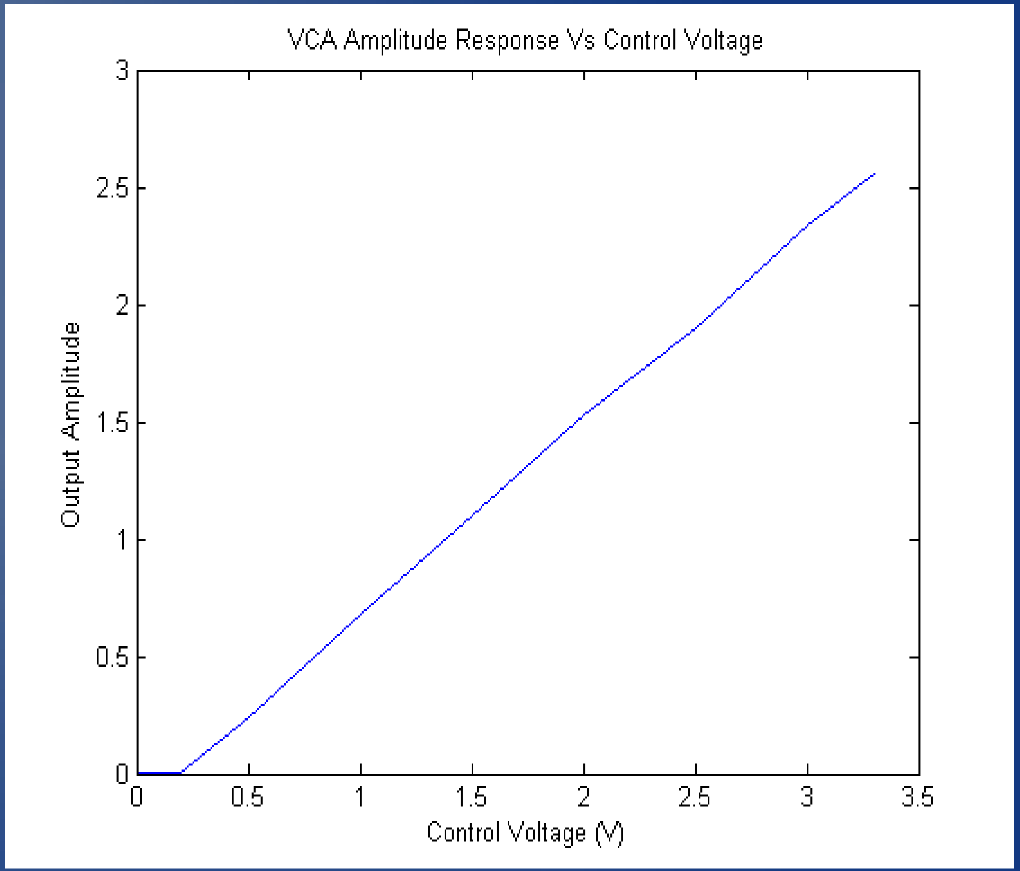

+3.3v
7
Vcc
MSP430F4132
Trig CH1
Trig CH2
Trig CH3
Trig CH4
Trig CH5
Trig CH6
Gate CH1
Gate CH2
Gate CH3
Gate CH4
Gate CH5
Gate CH6
FVC CH1
FVC CH2
FVC CH3
FVC CH4
FVC CH5
FVC CH6
27 P2.0/TA1.1/S15
26 P2.1/TA1.2/S14
25 P2.2/TA1.3/S13
24 P2.3/TA1.4/S12
23 P2.4/S11
22 P2.5/S10
42 P5.1/R23
41 P5.2/R13/LCDREF
40 P5.3/R03
39 P5.4/COM3
38 P5.5/COM2
37 P5.6/COM1
60 P7.4/TA1.4/A0/CA2
61 P7.5/TA1.3/A1/CA3
63 P6.0/TA1.2/A2/CA4
3 P6.3/A3/CA5/Veref-/Vref-
4 P6.4/A4/CA6/Veref+/Vref+
5 P6.5/UCA0RXD/UCA0SOMI/A5
R1
100k
R2
150k
Vss
10
P1.2/TA0.1/S29 51
P7.6/TA0.2/S25 45
P5.0/TA1.1/S24 44
P3.0/TA1.2/S23 35
P3.1/TA1.3/S22 34
P3.2/TA1.4/S21 33
R3
C1
330k
0.05uF
VCO CV1
VCO CV2
VCO CV3
VCO CV4
VCO CV5
VCO CV6

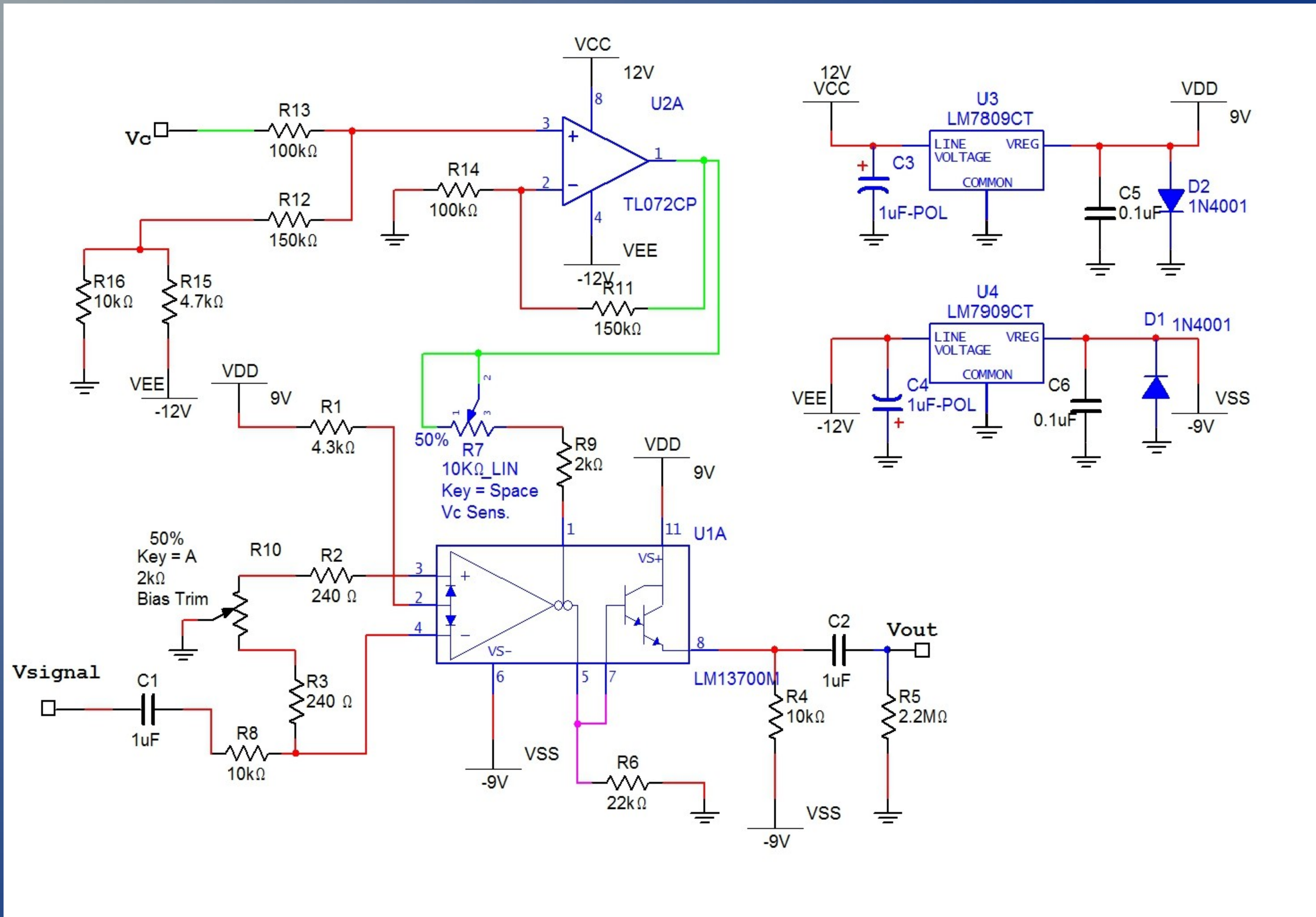
Voltage Controlled Amplifier (VCA)
Requirements

- To provide amplification that varies with a control voltage created by a contour generator
- Must be linear with respect to control voltage
- Have a flat frequency response of +/-1dB up to 20kHz
- Must produce undistorted output (no rail clipping)
- Minimum of unity gain
- Input offset voltage less than 1mV

Design

- VCA using the LM13700
- Input offset voltage of 0.4mV
- Control voltage is from the ADSR contour generator
- Control voltage will be amplified from 3.3V to about 5V and shifted down by about 8V from by an opamp



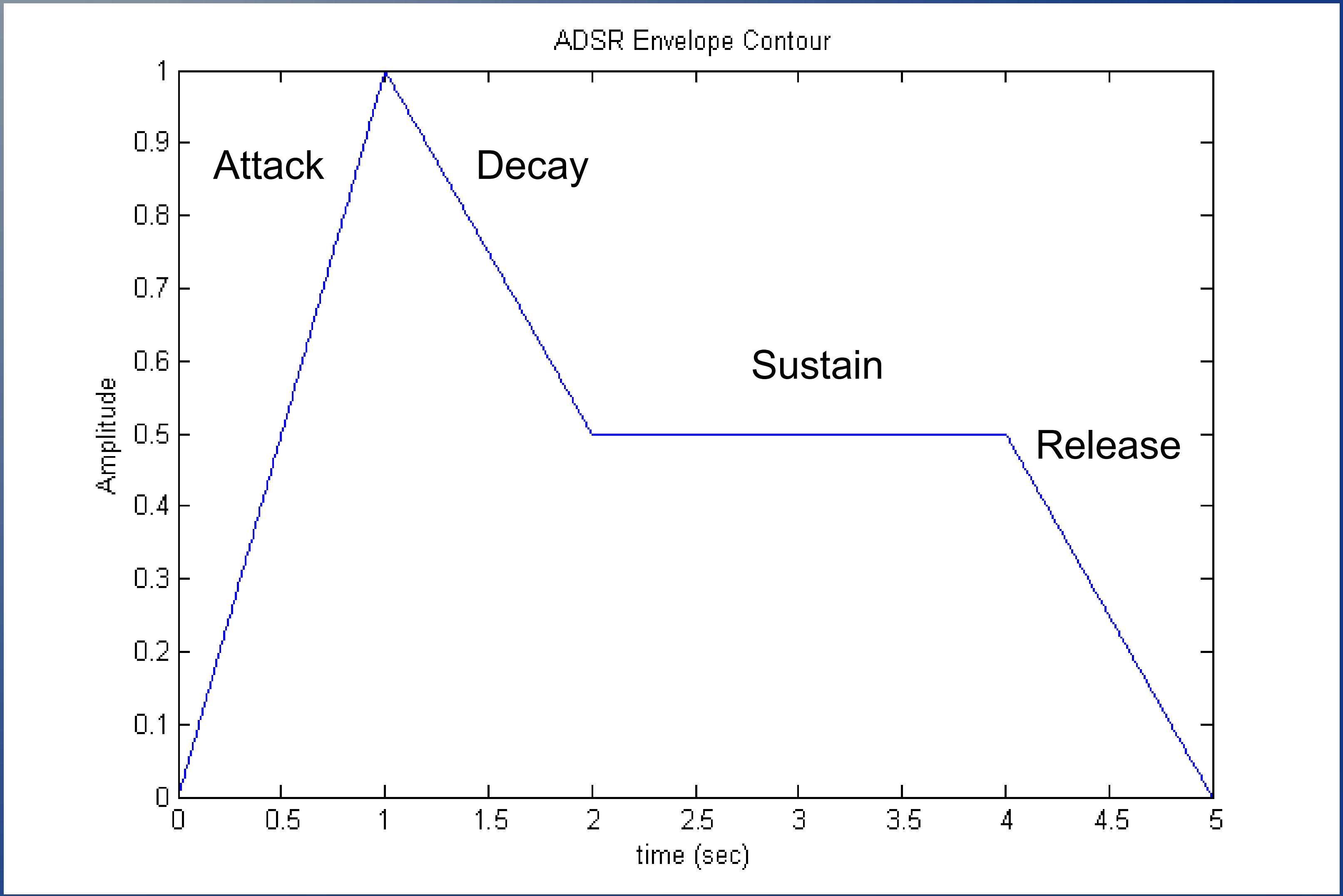

VCC
12V
U2A
8
Vc
R13
100kΩ
3
+
1
R14
2
−
100kΩ
TL072CP
R12
4
150kΩ
VEE
-12V
R11
R16
10kΩ
R15
4.7kΩ
150kΩ
VEE
-12V
VDD
9V
R1
4.3kΩ
50%
R7
10KΩ_LIN
Key = Space
Vc Sens.
R9
2kΩ
VDD
9V
11
U1A
VS+
50%
Key = A
2kΩ
Bias Trim
R10
R2
240 Ω
R3
240 Ω
Vsignal
C1
1uF
R8
10kΩ
VS−
6
5
7
8
LM13700M
VSS
-9V
R6
22kΩ
C2
1uF
Vout
R4
10kΩ
R5
2.2MΩ
VSS
-9V
12V
VCC
U3
LM7809CT
LINE VOLTAGE
VREG
COMMON
C3
1uF-POL
VDD
9V
C5
0.1uF
D2
1N4001
U4
LM7909CT
LINE VOLTAGE
VREG
COMMON
D1
1N4001
VEE
-12V
C4
1uF-POL
C6
0.1uF
VSS
-9V

Envelope Generator

ADSR – Attack, Decay, Sustain, Release

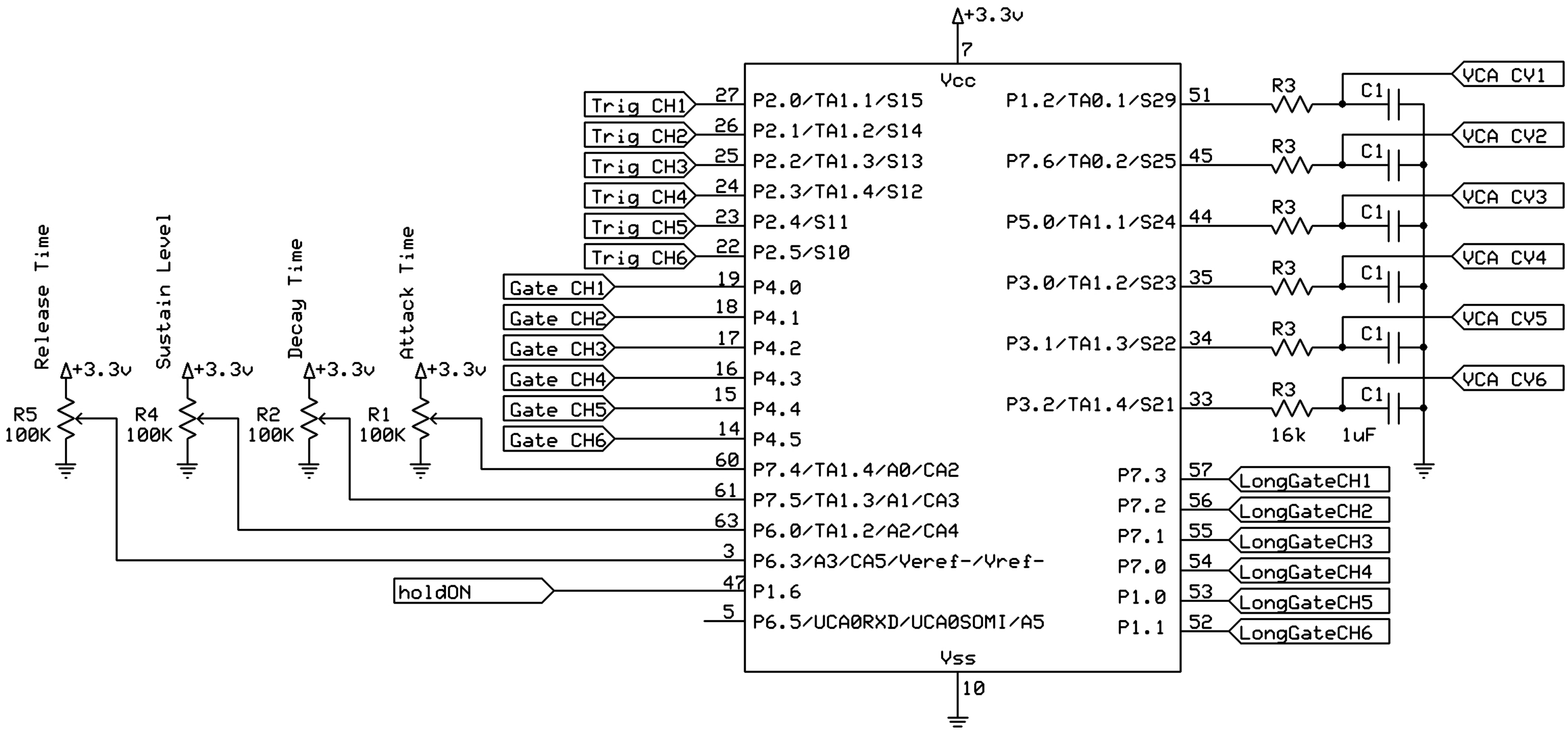
- Provide a user controlled contour generator
- Wide range of attack/decay/release times - 50ms to 5s
- Will provide user with numerous contour options from short, staccato to slow volume swells
- External controls are
  - Attack time – initial volume rise time
  - Decay time – time to fall to sustain level
  - Sustain level
  - Release time – time to fall to zero volume after note is release (string muted)

General ADSR Shape



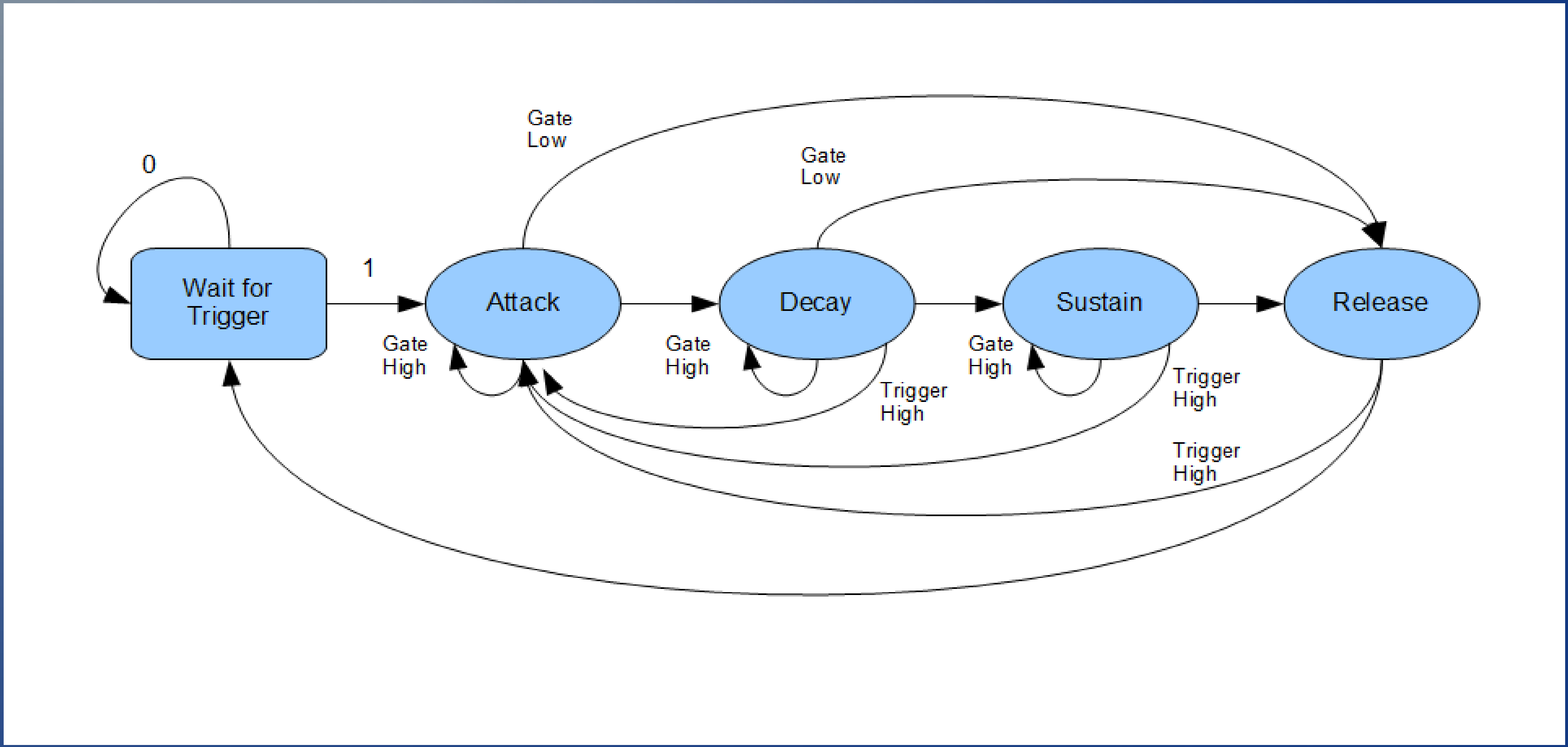
Design

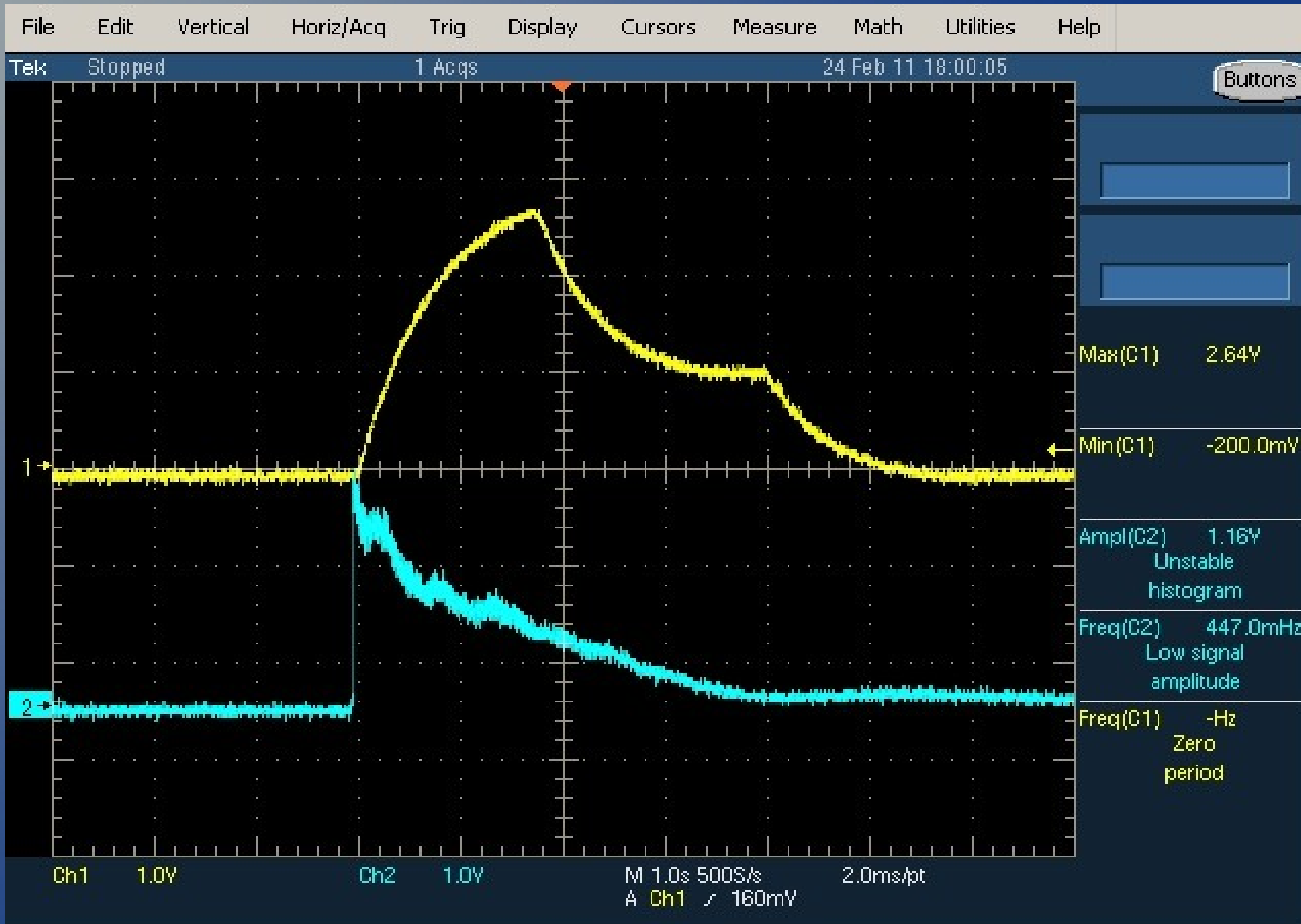
- MSP430F4132
- 6 PWM outputs, one for each channel's contour, 15.6kHz
- Will use 4 ADC pins for reading potentiometer positions
- ADC pins sampled every 32ms
- Will accept triggers and gates for each channel
- Utilizes wave tables for rising and falling exponential curves, simulating analog synthesizer ADSRs
- Also, the ear hears logarithmically, so an exponential shape in volume sounds more linear
- Time is sped up by skipping samples (principle of direct digital synthesis)



- Triggers as port pin edge interrupts
- Gates as GPIO
- Potentiometers into ADC ports
- PWM outputs filtered at about 10Hz

ADSR Software Flow

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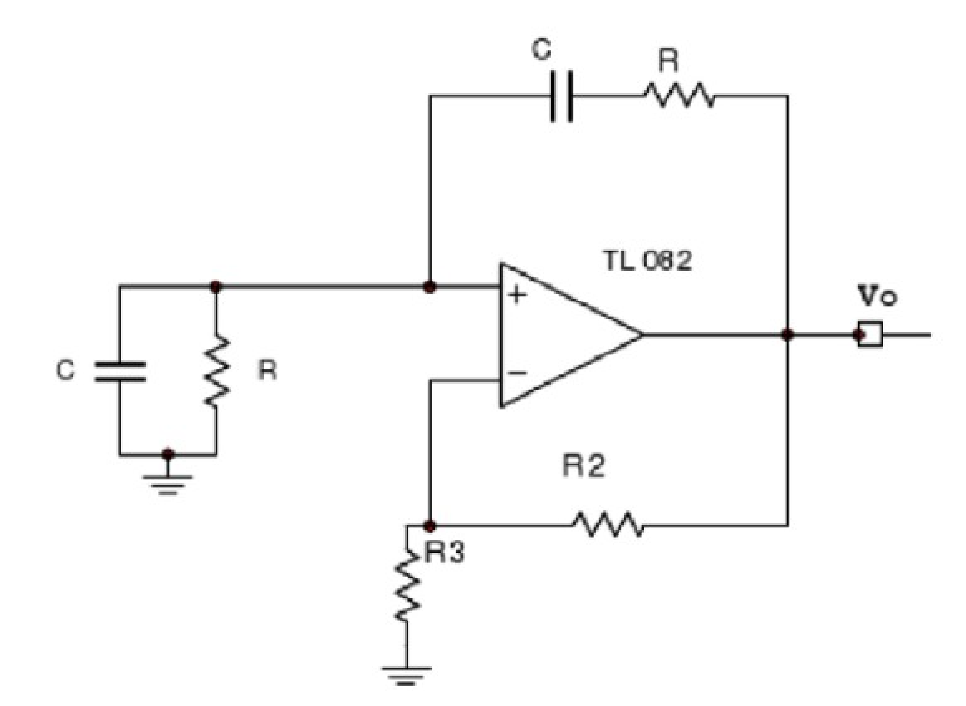
24 Feb 11 18:00:05
Buttons
Max(C1) 2.64V
Min(C1) -200.0mV
Ampl(C2) 1.16V
Unstable histogram
Freq(C2) 447.0mHz
Low signal amplitude
Freq(C1) -Hz
Zero period
Ch1 1.0V
Ch2 1.0V
M 1.0s 500S/s 2.0ms/pt
A Ch1 ⟋ 160mV

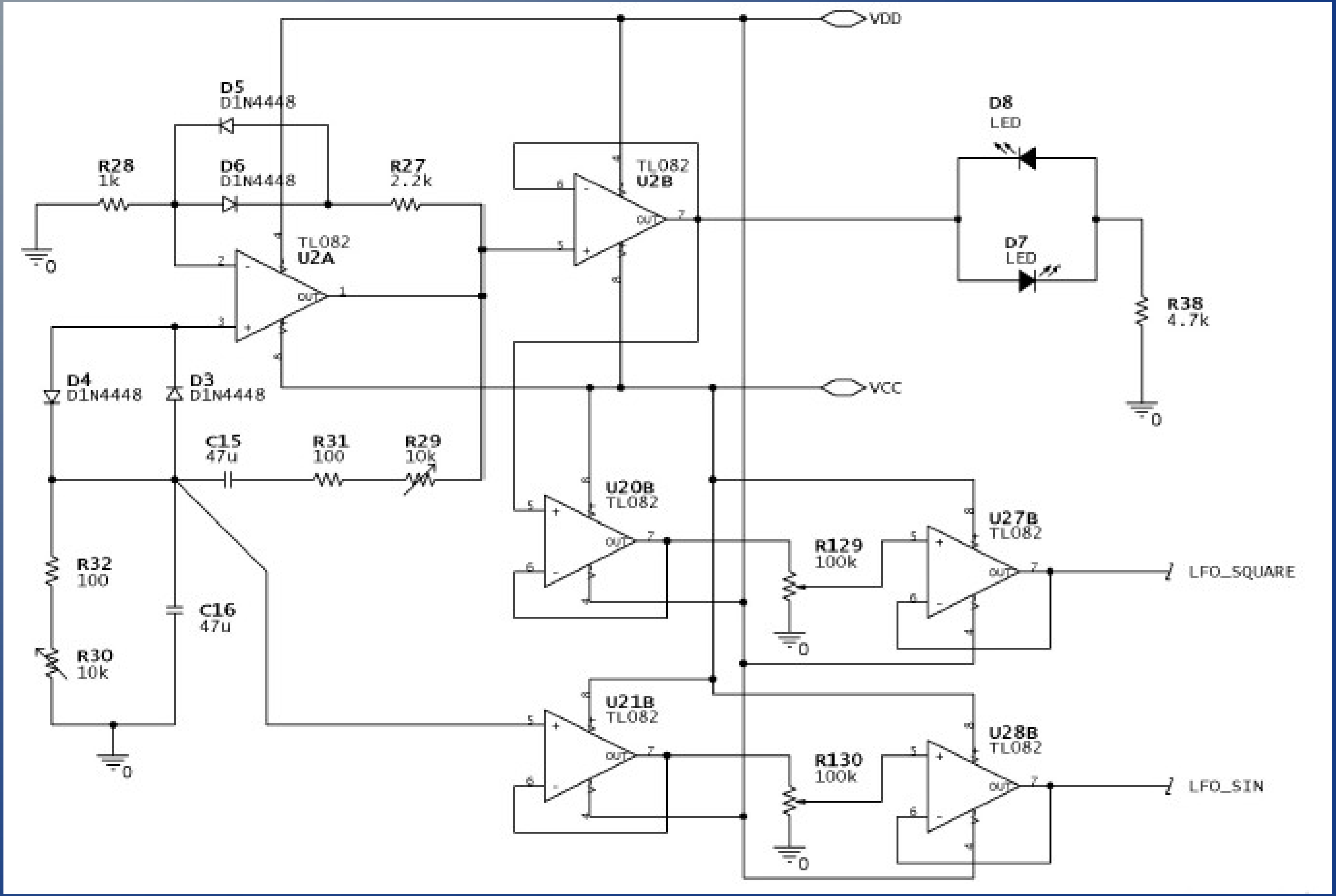
Low Frequency Oscillator

- Based on a Wein-Bridge Oscillator.
- Produces frequencies from 3Hz to 33Hz.
- Produces both a sin wave and square wave oscillation, depending on where the signal is taken from.
- Will be used by vibrato, tremolo and the arpeggiator
- Independent of other designs, tracking is not an important issue.



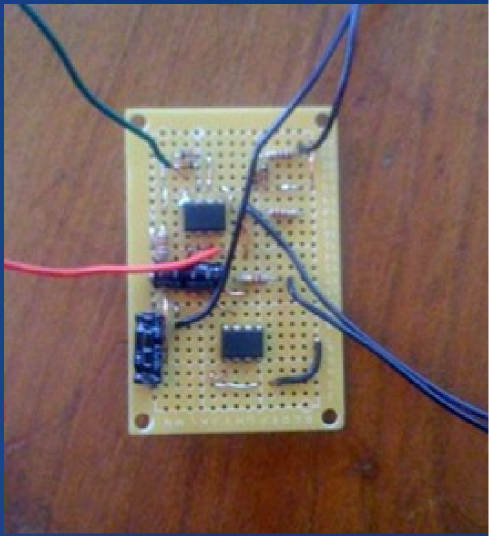
$$F_o = \frac{1}{2\pi RC}$$

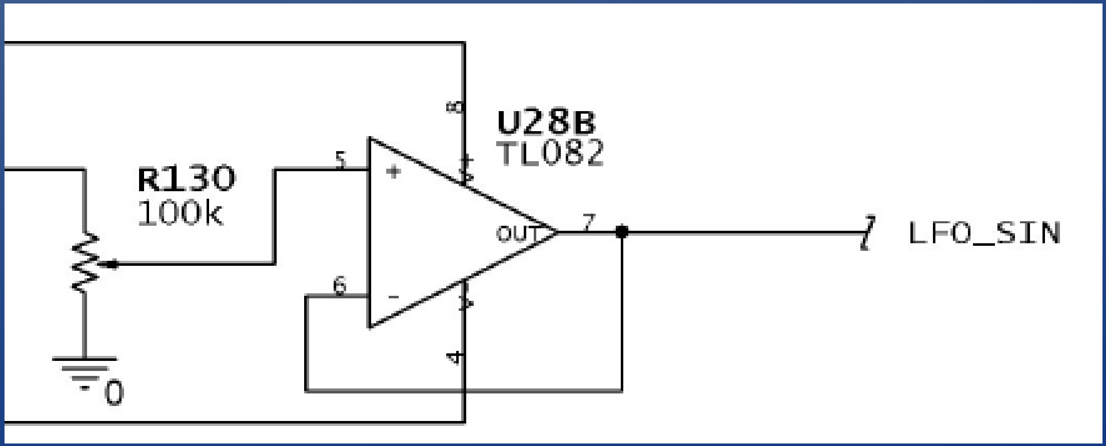
LFO Schematic



LFO Rate and Depth

- Two potentiometers control the rate of oscillation. If they are Low the new resistance becomes 100 Ohms and the frequency is 33.3Hz. If they are high high the new resistance becomes 1100 Ohms and the frequency is 3.3 Hz.
- The amplitude of the LFO will be controlled independently for each effect.

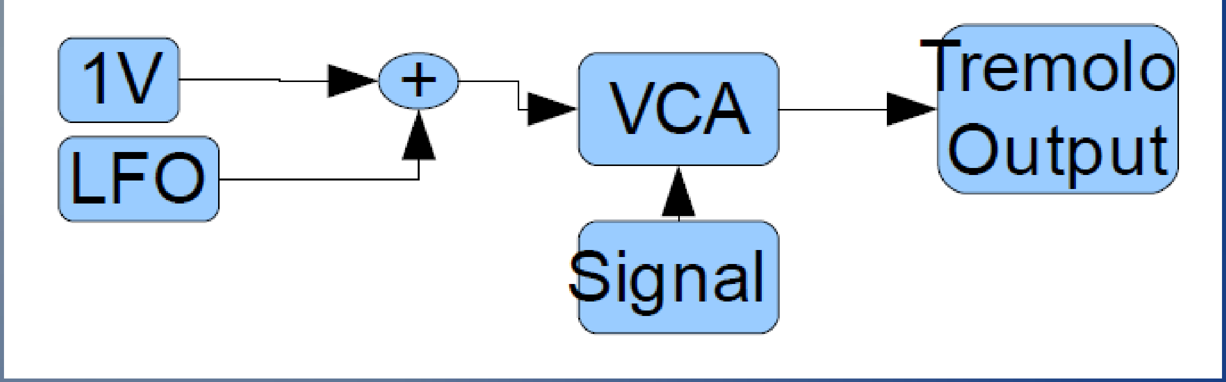


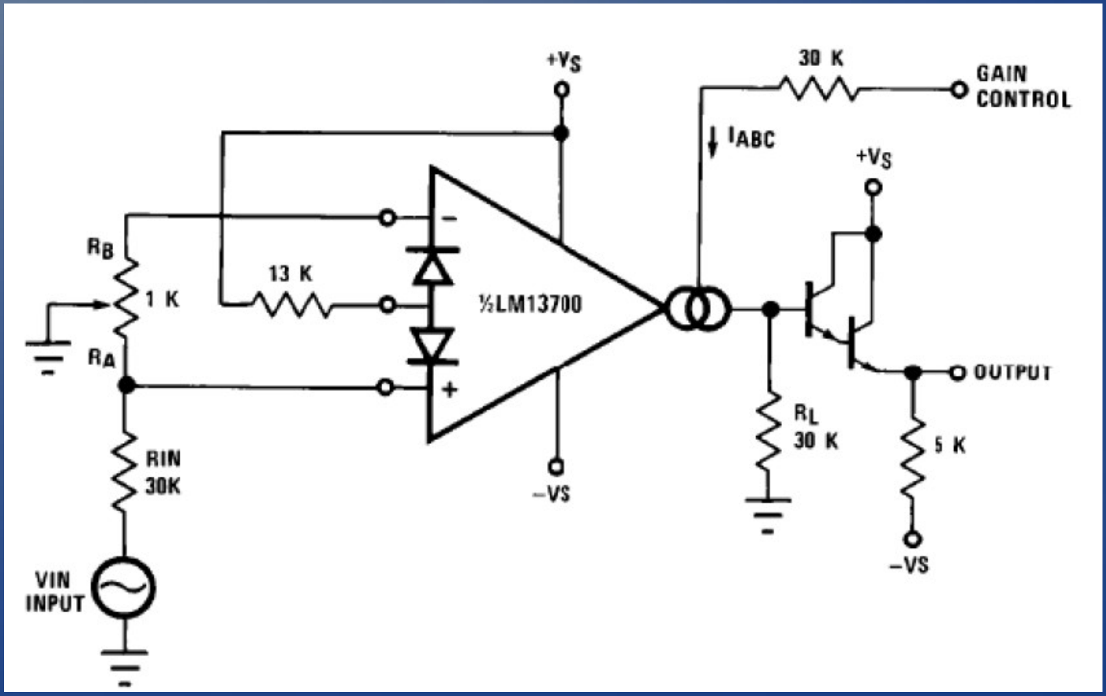


Tremolo

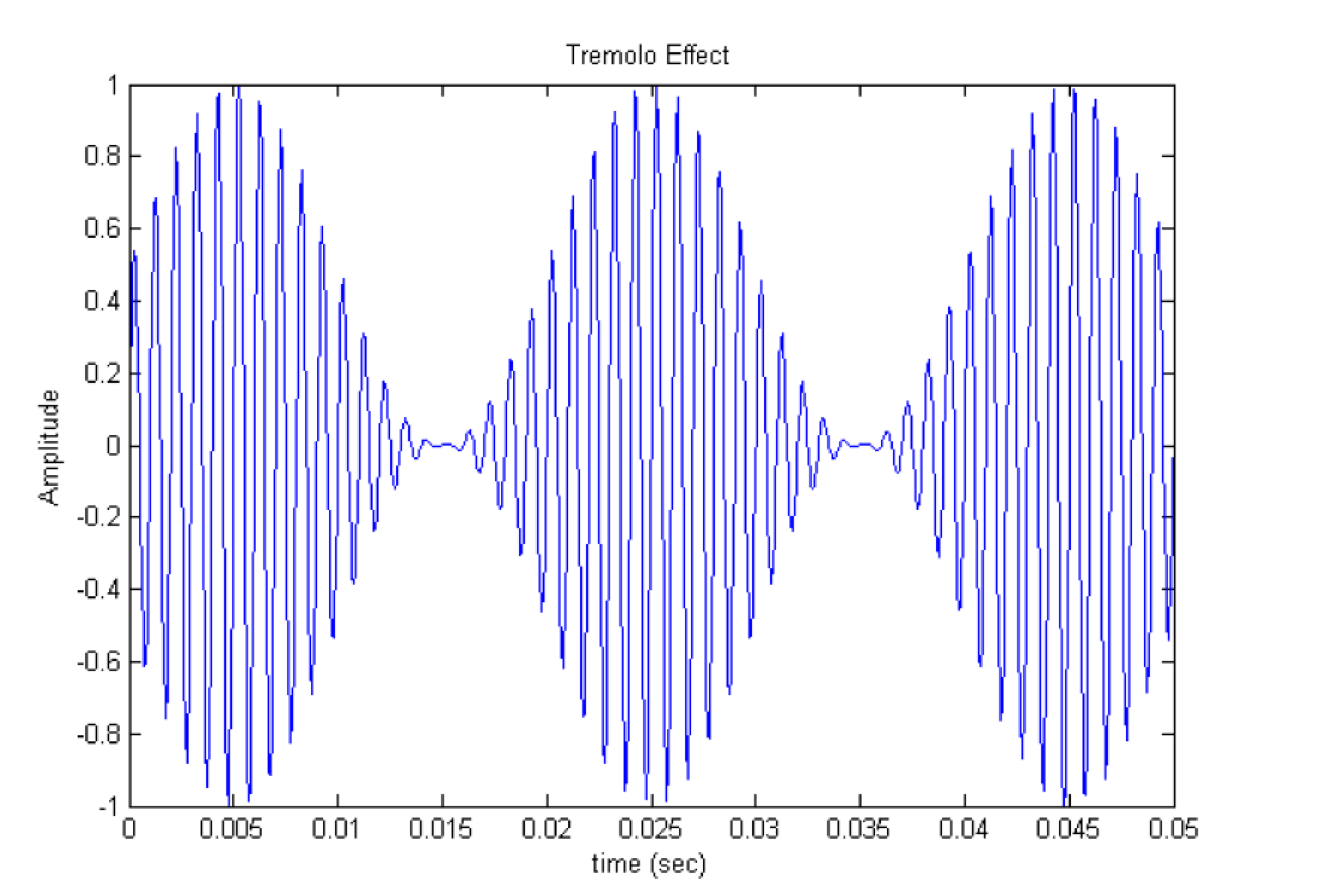
- Rapid increase and decrease in the amplitude (volume) of a signal.
- A signal is buffered from the LFO an adjustable amplitude (depth) and a maximum of 1V pk-pk and is used as the gain control.
- Added with a DC voltage of 1v. If the depth is set at its maximum. The signal will completely be attenuated when the LFO is negative
- The potentiometer is adjusted to minimize the effects of the control signal at the output

Tremolo


1V
+
LFO
VCA
Signal
Tremolo Output


+VS
30 K
GAIN CONTROL
IABC
+VS
RB
1 K
13 K
½LM13700
RA
OUTPUT
RL 30 K
5 K
RIN 30K
–VS
–VS
VIN INPUT

Tremolo

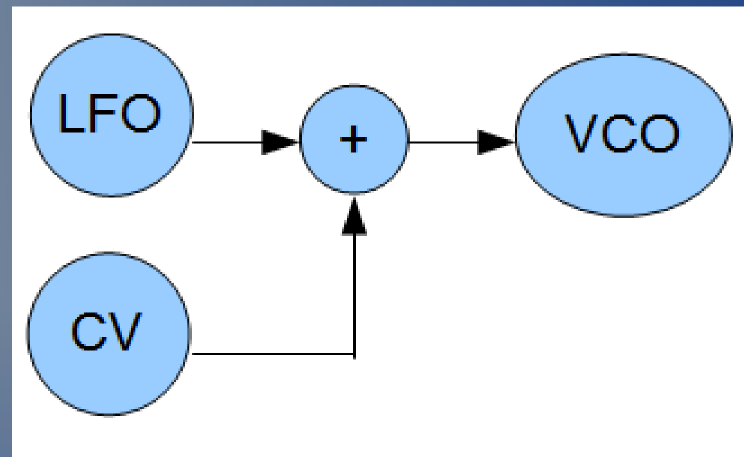


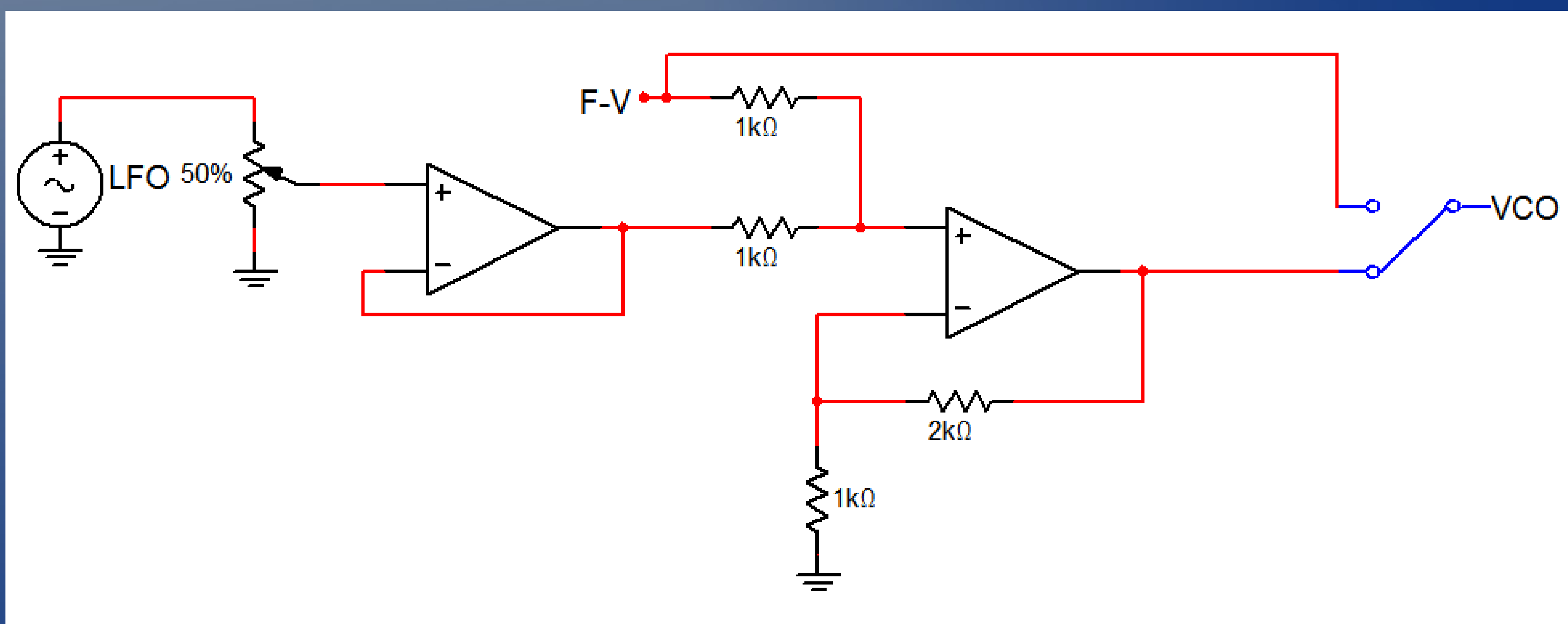
Sine wave LFO applied to control the amplitude of the signal. As the rate is increased on the LFO the rate of modulation changes as well.

Vibrato

- Increase and decrease in frequency (pitch) of a signal.
- This is done by attenuating the signal from the LFO and adding it to the output of the F-V using the summing op-amp configuration.
- Every string has its own independent summer. Resulting in 6 SPDT or 3 DPDT (each controlling two strings) so the effect can be turn on for some strings and off for others

Vibrato



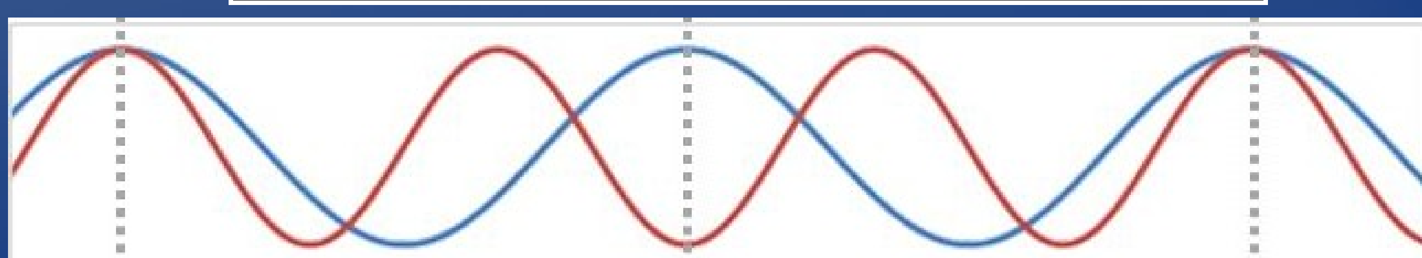


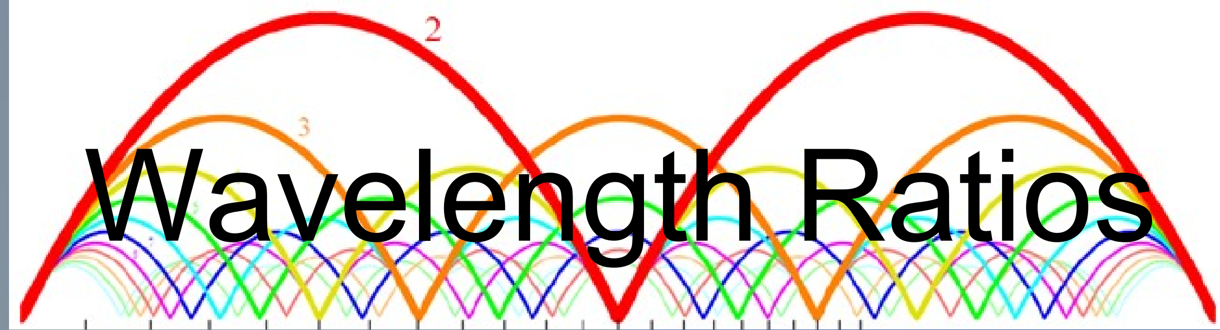
Arpeggiator

- Automatically steps through a sequence of notes based on the input note, thus creating an arpeggio.
- This feature takes advantage of the linearity between the F-V converter and the VCO.
- ex. If an input frequency of 41.20 Hz (E) outputs a dc voltage of 1.6V, in order to hit the next E octave (82.41 Hz) on the VCO the output voltage of 1.6V would need to be doubled to 3.2V.
- Major chord – root, major 3rd, perfect 5th.
- Minor chord – root, minor 3rd, perfect 5th.

Arpeggiator

Note	Ratio	Interval
0	1:1	Unision
1	16:15	Major semitone
2	9:8	Major 2nd
3	6:5	Minor 3rd
4	5:4	Major 3rd
5	4:3	Perfect 4th
6	45:32	Diatonic tritone
7	3:2	Perfect 5th
8	8:5	Minor 6th
9	5:3	Major 6th
10	9:5	Minor 7th
11	15:8	Major 7th
12	2:1	Octave





Wavelength Ratios

- Single op-amp non inverting gain configuration takes the F-V signal and applies the appropriate gain to each line
- Root – 1:1 no multiplication required
- Major 3rd – 5:4 requires x 1.25
- Perfect 5th – 3:2 requires x 1.5
- Octave – 2:1 requires x 2
- Analog 4:1 Mux 74FST3253 offers high frequency response with 7.5 nS switching times.
- Operates from -.5v to 7v

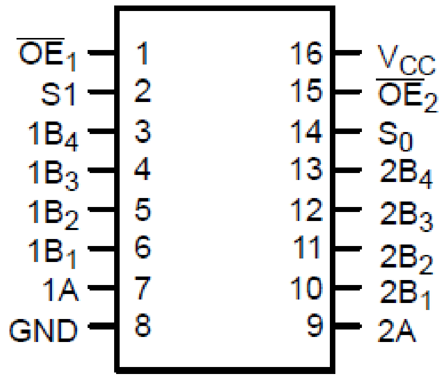
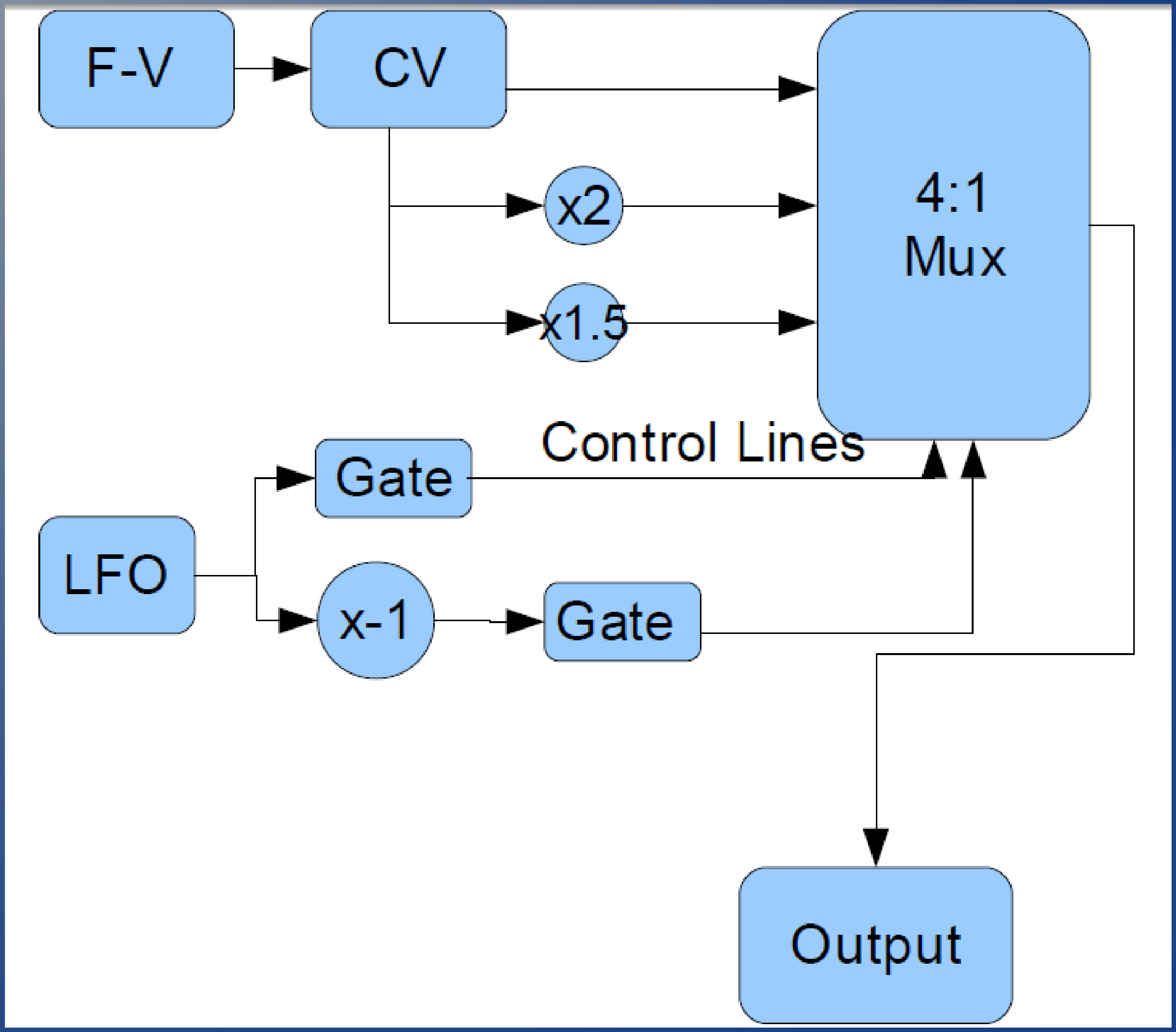


Figure 1. 16–Lead Pinout

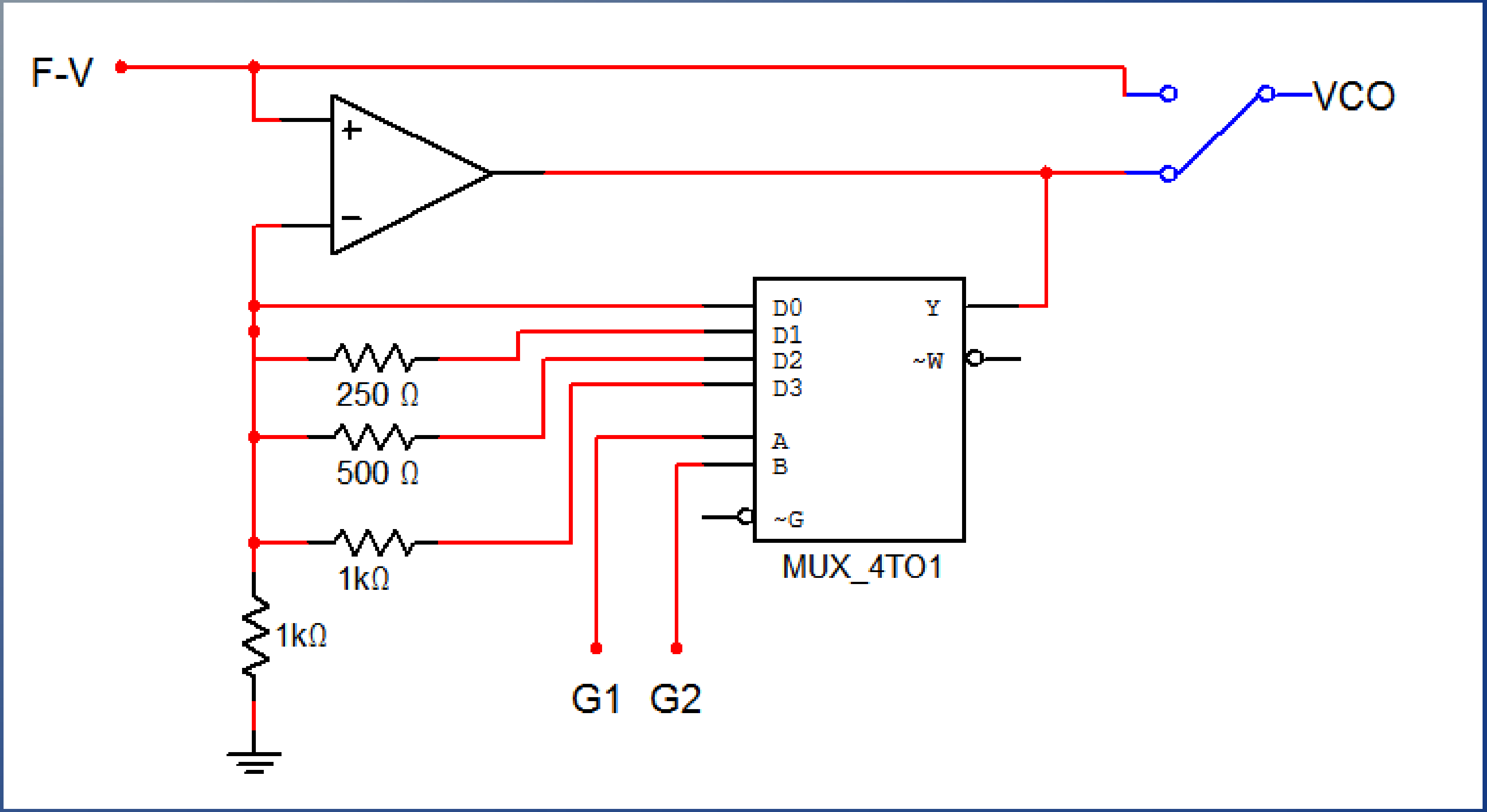
S_1	S_0	$\overline{OE}_1$	$\overline{OE}_2$	Function
X	X	H	X	Disconnect 1A
X	X	X	H	Disconnect 2A
L	L	L	L	$A = B_1$
L	H	L	L	$A = B_2$
H	L	L	L	$A = B_3$
H	H	L	L	$A = B_4$

Figure 2. Truth Table

Arpeggiator Block Diagram



Arpeggiator

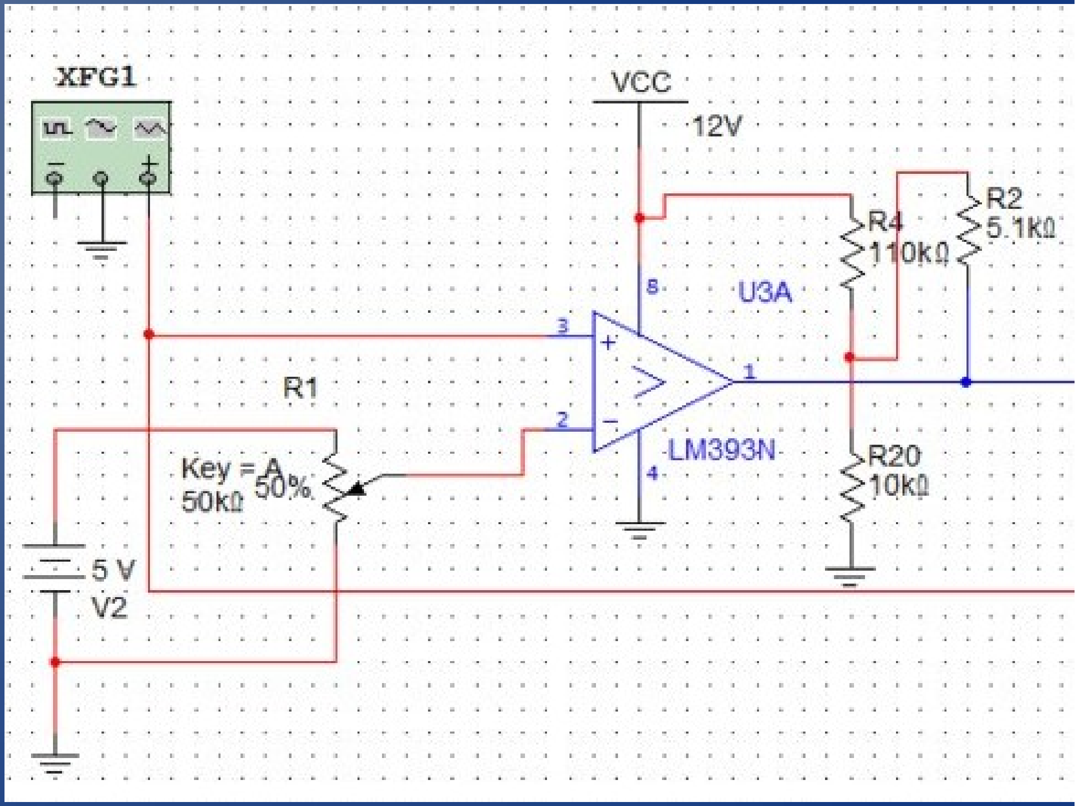


4:1 Mux Control Lines

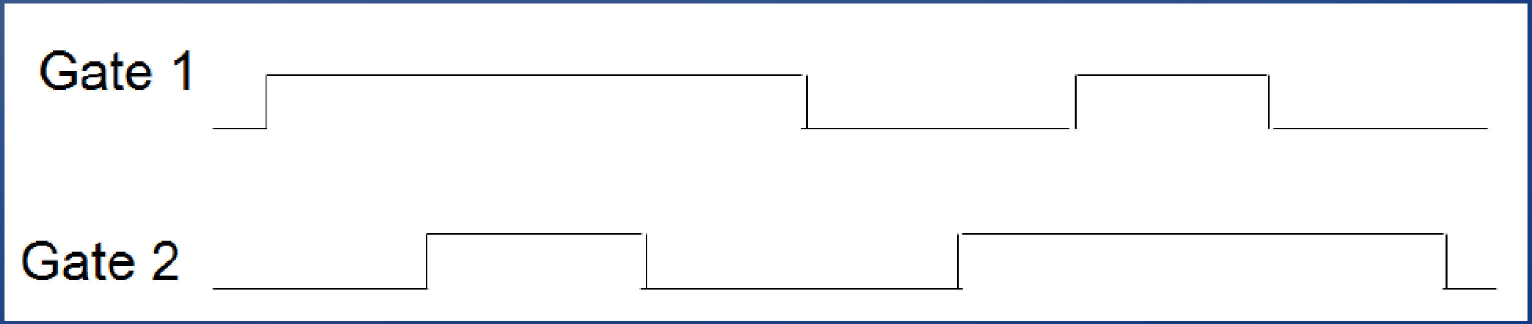
- Uses a rectified signal from the LFO with a normalized amplitude of 2V through two gates with different adjustable threshold voltages.
- When the LFO voltage is below the threshold voltage G1 the output is Vlow.
- When the LFO voltage is higher the threshold voltage on G1 the gate outputs Vhigh.

Schmitt Trigger Comparator

- There is only 2 gates that control the arpeggiation of all 6 strings.
- Potentiometer controls the threshold voltage and passes it through a comparator.



Control Lines

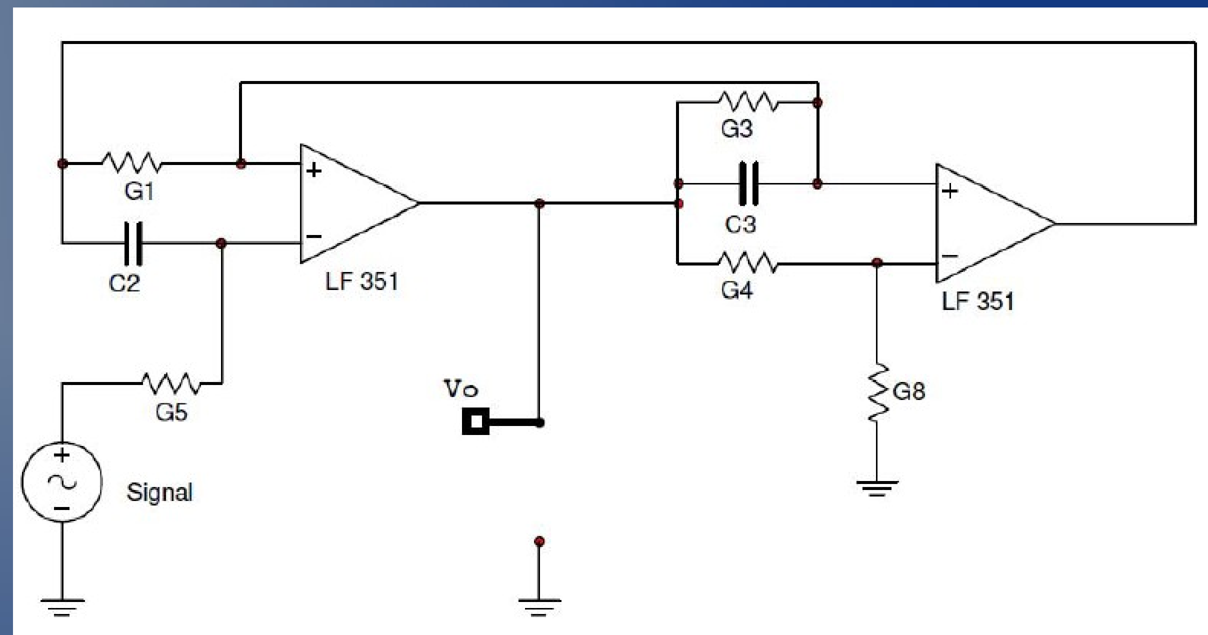


Cutoff and Resonance Filter

- A low pass filter where the user has the ability to tune where the cutoff frequency is (between 10 Hz and 1.2Khz).
- A filter that has the ability for the user to tune how much resonance is desired on the output.
-

CGIC

- Based on Dr. Wasfy Mikhael CGIC LP filter design.
- If G3 is tuned only the resonance changes.
- If G4 or G8 is tuned the gain, cutoff and resonance are affected.

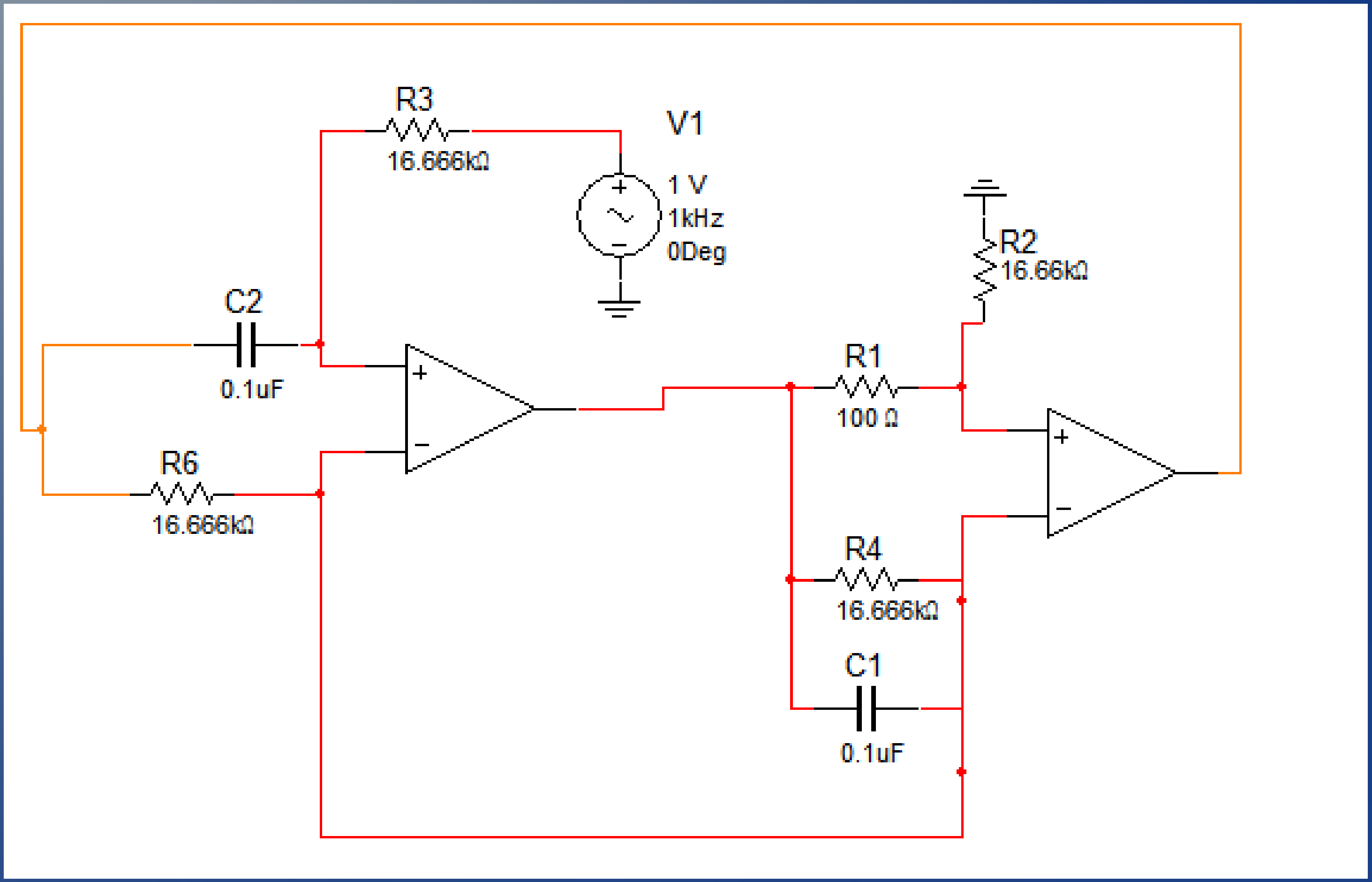


$$T(s)=\frac{1+\frac{G_8}{G_4}}{s^2\frac{C_2C_3G_8}{G_1G_5G_4}+s\frac{C_2G_3G_8}{G_1G_5G_4}+1}$$

$$w_p^2=\frac{G_1G_5G_4}{C_2C_3G_8}$$

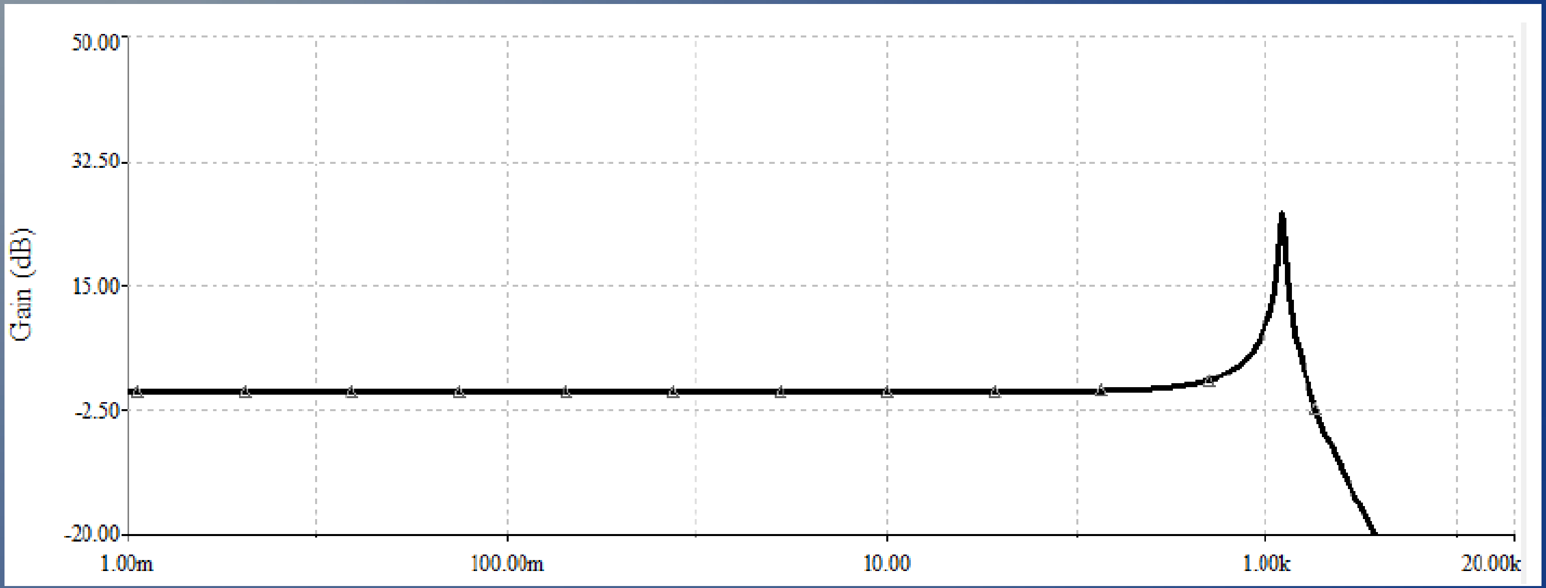
$$Q_p^2=\frac{C_3G_1G_4G_5}{C_2G_3^2G_8}$$

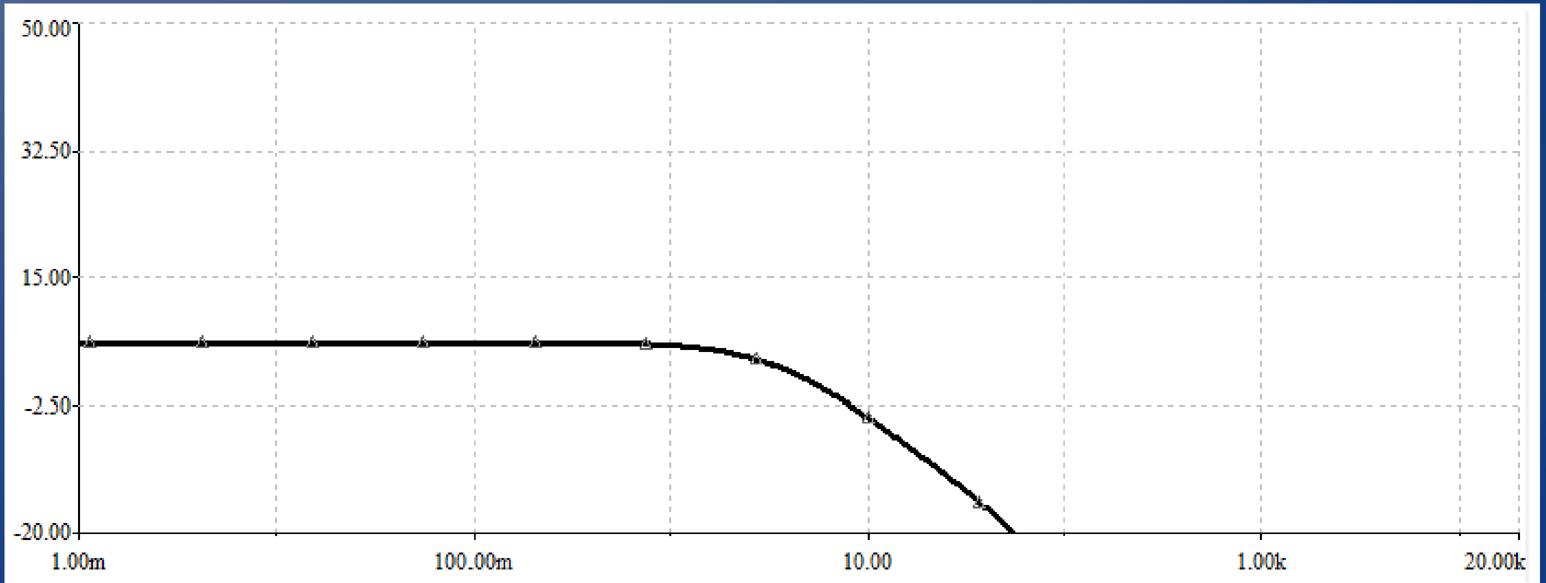
CGIC



R3
16.666kΩ
V1
1 V
1kHz
0Deg
R2
16.66kΩ
C2
0.1uF
R1
100 Ω
R6
16.666kΩ
R4
16.666kΩ
C1
0.1uF

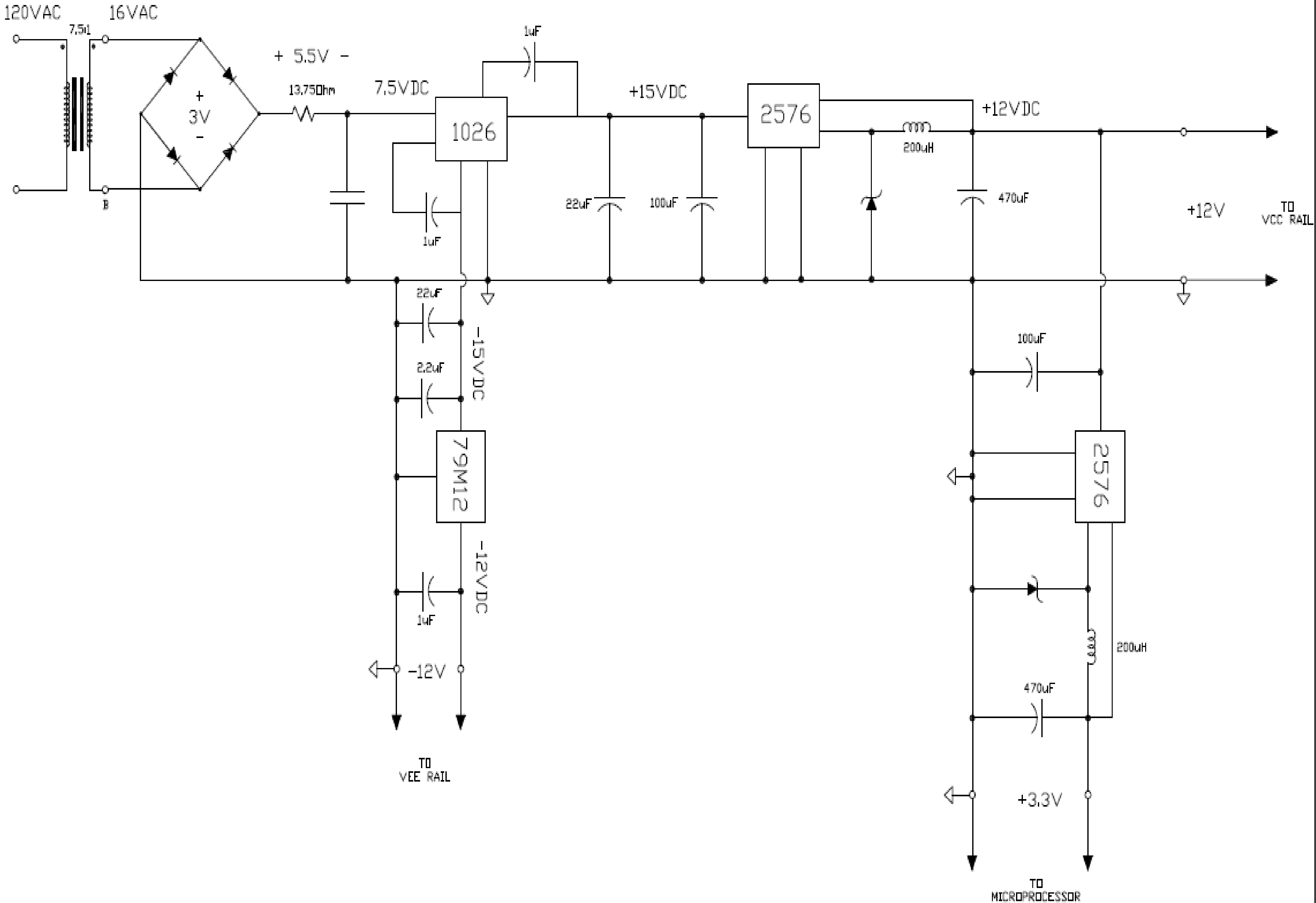
Cutoff and Resonance





Power Supply Requirements

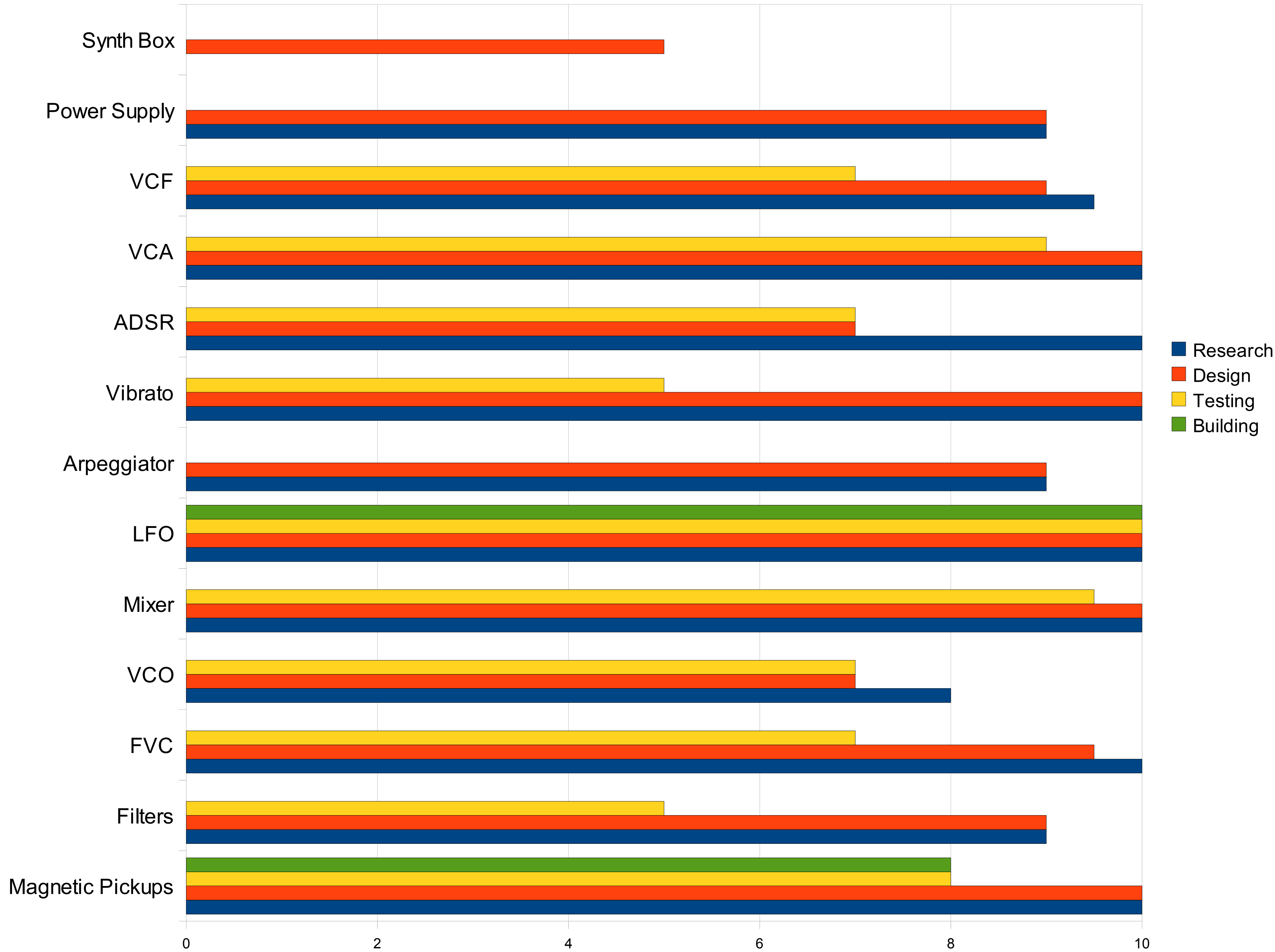
- Supply +/-12Vdc and +3.3Vdc
- 1.0A<A<2.0A from +/-12V supply
- 250mA<A<1.0A from +5V supply


120VAC
16VAC
7.5:1
B
+ 3V -
+ 5.5V -
13.75Ohm
7.5VDC
1uF
1026
1uF
+15VDC
22uF
100uF
2576
+12VDC
200uH
470uF
+12V
TO
VCC RAIL
22uF
2.2uF
-15VDC
79M12
-12VDC
1uF
-12V
TO
VEE RAIL
100uF
2576
200uH
470uF
+3.3V
TO
MICROPROCESSOR

Parts Required

- 1 PCB transformer (120VAC:16VDC)
- 2 LM2576 switching regulators
- 1 LM79M12 negative voltage regulator
- LT1026 DC-DC voltage converter
- 10 Capacitors
- 1 Resistor
- 2 Inductors
- 2 Schottky diodes
- 3 Heat sinks--8.9degC/W

Progress



Synth Box
Power Supply
VCF
VCA
ADSR
Vibrato
Arpeggiator
LFO
Mixer
VCO
FVC
Filters
Magnetic Pickups
0
2
4
6
8
10
Research
Design
Testing
Building

Part	Qty.	Cost ea.	# Bought	$ Spent	Projected Cost
ICs					
LM13700	8	$1.50	8	$12.00	$12.00
511-TL081CN	40	$0.58	20	$11.16	$23.20
LM2902KNE4	6	$0.51	6	$3.06	$3.06
LM2907	6	$1.86	2	$3.72	$11.16
TL072	2	$0.69	0	$0.00	$1.38
TL074	5	$0.99	0	$0.00	$4.96
NJM13700M	3	$1.02	3	$3.06	$3.06
LM339	3	$0.49	0	$0.00	$1.47
MSP430F4132	1	$4.56	1	$4.56	$4.56
UA78L09ACLP	1	$0.58	0	$0.00	$0.58
KA7909TU	1	$0.63	0	$0.00	$0.63
LM2576	2	$2.24	2	$4.48	$4.48
LM79M12	1	$0.61	1	$0.61	$0.61
LT1026	1	$2.50	1	$2.50	$2.50
4:1 Multiplexer	1	$7.00	1	$7.00	$7.00
Total				$52.15	$80.65
Small Components					
Resistors	556	$0.06	0	$0.00	$33.34
Capacitors	73	$0.19	0	$0.00	$13.87
Inductors	2	$0.28	2	$0.56	$0.56
Schottky Diodes	2	$1.00	2	$2.00	$2.00
1N4148 Diodes	10	$0.02	0	$0.00	$0.20
1N4001	2	$0.16	0	$0.00	$0.32
LEDs	12	$0.10	0	$0.00	$1.20
Total				$0.00	$51.49
Potentiometers					
Trim Pot	32	$0.50	0	$0.00	$16.00
Panel Pot	4	$1.25	0	$0.00	$5.00
Slide Pot	12	$2.08	12	$24.96	$24.96
Total				$24.96	$45.96

Boards					
Dev Board	1	$4.30	1	$4.30	$4.30
LQFP 64 PCB Adapter	1	$1.75	1	$1.75	$1.75
Through-hole PCB	5	$3.00	1	$3.00	$15.00
Copper-plated Board	6	$5.00	0	$0.00	$30.00
Total				$9.05	$51.05
Hardware					
DPDT Toggle Switch	7	$2.92	6	$17.52	$20.44
SPDT Toggle Switch	1	$0.00	1	$0.00	$0.00
Heat Sinks	3	$0.85	3	$2.55	$2.55
Transformer	1	$8.35	1	$8.35	$8.35
AlNiCo Magnets and Magnetic wire		$10.00	1	$10.00	$10.00
VGA Connectors	1	$6.00	1	$6.00	$6.00
VGA Cable	1	$0.00	1	$0.00	$0.00
Power Supply Box	1	$6.00	0	0	$6.00
Power Supply Tri-Cable	1	$8.00	0	$0.00	$8.00
Total				$44.42	$61.34
			Initial Estimate	Total Spent	Projected Total
			$212.04	$130.58	$290.49