SSM2164 SVF

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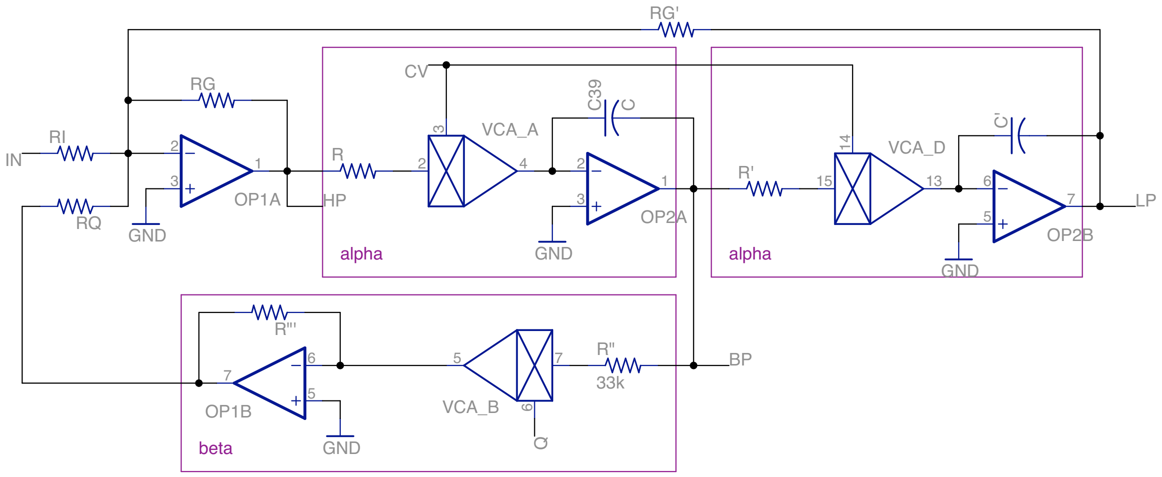


1 Theory

Notations:

R_i is the value of the resistor through which the input signal is fed to the circuit.

R_g is the value of the resistors through which the HP and LP outputs are fed back into the input.

R_q is the value of the resistor through which the attenuated BP output is fed back into the input.

R is the value of the resistors through which input voltages are converted into currents at the input of the 2164s, and through which the current at the output of the Q attenuator is converted back into a voltage.

C is the value of the integrators' capacitors.

v_{cv} is the cutoff frequency control voltage and v_q is the reso control voltage.

The input voltage is $v_i(s)(s)$. $v_{lp}(s)$, $v_{hp}(s)$, $v_{bp}(s)$ are respectively the voltages at the low-pass, high-pass and band-pass nodes of this circuit.

As a reminder, the transfer function of a SSM2164 gain cell is $i_{out} = i_{in}10^{-\frac{3}{2}v_{cv}}$. The transfer function of an integrator cell α is thus the following:

$$\alpha(s) = -\frac{1}{RCs}10^{-\frac{3}{2}v_{cv}} \tag{1}$$

We also have: $v_{bp}(s) = v_{hp}(s)\alpha(s)$, and $v_{lp}(s) = v_{hp}(s)\alpha^2(s)$.

The gain of the feedback circuit is noted β:

$$\beta = \frac{1}{R}10^{-\frac{3}{2}v_q} \times -R = -10^{-\frac{3}{2}v_q} \tag{2}$$

Since the op-amp has a huge input impedance, we can assume that the current flowing into i^- is null:

$$\frac{v_i(s) - v^-}{R_i} + \frac{v_{hp}(s) - v^-}{R_g} + \frac{v_{lp}(s) - v^-}{R_g} + \frac{v_{lp}(s) - v^-}{R_g} + \frac{v_{bp}(s)\beta - v^-}{R_q} = i^- = 0 \quad (3)$$

The voltages at the inputs of the op-amp being equal, $v^-(s) = v^+(s) = 0$, hence:

$$\frac{v_i(s)}{R_i} + \frac{v_{hp}(s)}{R_g} + \frac{\alpha^2(s)v_{hp}(s)}{R_g} + \frac{v_{hp}(s)\alpha(s)\beta}{R_q} = 0 \quad (4)$$

The transfer function for the HP mode can be deduced from there:

$$\begin{aligned} H_{hp}(s) &= \frac{v_{hp}(s)}{v_i(s)} && (5) \\ &= \frac{-1/R_i}{\frac{1}{R_g} + \frac{\alpha^2(s)}{R_g} + \frac{\alpha(s)\beta}{R_q}} && (6) \\ &= \frac{-R_g/R_i}{1 + \frac{R_g\alpha(s)\beta}{R_q} + \alpha^2(s)} && (7) \\ &= \frac{-G}{1 + \frac{R_g\alpha(s)\beta}{R_q} + \alpha^2(s)} && (8) \end{aligned}$$

$G = \frac{R_g}{R_i}$ is the absolute value of the pass-band gain. For further simplifications, we assume $R_g = 2R_q$.

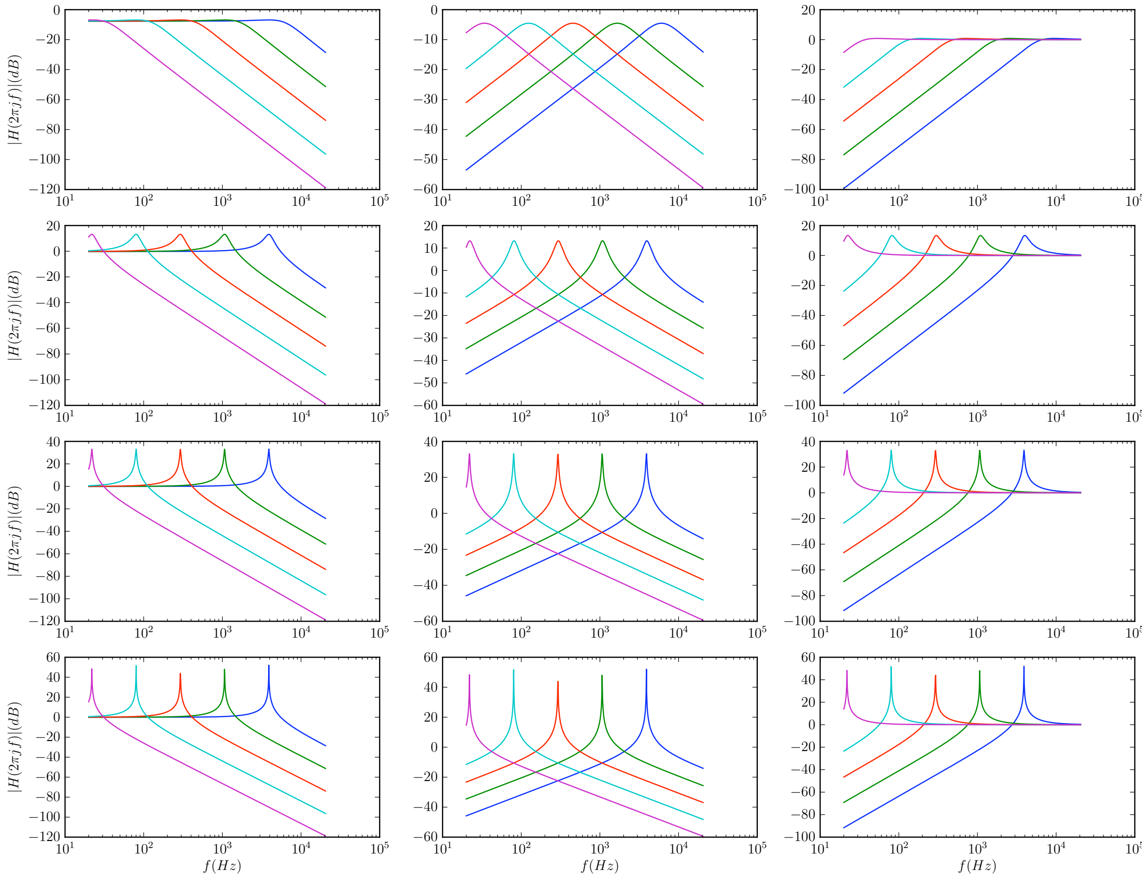
The transfer function for the LP mode is:

$$\begin{aligned} H_{lp}(s) &= \frac{v_{lp}(s)}{v_i(s)} && (9) \\ &= \frac{v_{hp}(s)}{v_i(s)}\alpha^2(s) && (10) \\ &= \frac{-G}{\frac{1}{\alpha^2(s)} + \frac{2\beta}{\alpha(s)} + 1} && (11) \\ &= \frac{-G}{\frac{s^2}{\left(\frac{1}{RC}10^{-\frac{3}{2}v_{cv}}\right)^2} + 2\frac{s}{\left(\frac{1}{RC}10^{-\frac{3}{2}v_{cv}}\right)}10^{-\frac{3}{2}v_q} + 1} && (12) \end{aligned}$$

By identification with the canonical form of a 2-nd order filter transfer function, this gives the following filter characteristics:

- Pass-band gain, $-G = -\frac{R_g}{R_i}$
- Cutoff frequency, $f = \frac{1}{2\pi RC}10^{-\frac{3}{2}v_{cv}}$
- Q factor, $Q = \frac{1}{2}10^{\frac{3}{2}v_q}$

Now, let us unleash the power of matplotlib and plot the filter response for several values of Q (rows), for the three modes (columns), and for 5 different cutoff settings (plots within a cell):



2 Practice

2.1 CV tuning

Because it operates with small supplies ($\pm 5V$) and has its control signals living in the $[0, 5]V$ range, the Shruthi-1 uses the unusual $5V$ = 128 midi notes scale, rather than the more common $1V$/octave scale – which would be too narrow in this context. This implies a $2^{\frac{128}{12}} = 1625.5$ ratio between the lowest and highest cutoff frequencies reached by the filter. Using the relationship between cutoff frequency and v_{cv}, this implies that v_{cv} swings by 2.141V between its smallest and highest value. The CV output by the Shruthi-1 has a 5V range, so the CV scaling circuit needs to have a $2.141/5 = 0.4282$ gain. This is more or less achieved by a $15k\Omega$ / $35k\Omega$ ratio, the $35k\Omega$ being obtained by a $33k\Omega$ resistor in series with a roughly centered $5k\Omega$ trimmer.

2.2 1-pole filter on resonance CV

The control signals generated by the Shruthi-1 are PWM modulated ; their 39kHz carrier needs to be removed by a low-pass filter. Cutoff signal conditioning is a serious matter, since the users want to calibrate the cutoff response to get tuned self-oscillation across several octaves. We cannot avoid dedicating PCB space to trimmers and a proper op-amp based cutoff CV scaling circuit.

When it comes to resonance, this is a different matter. The board space was limited and we did not have enough room to implement a proper active filter for smoothing the resonance CV. We went cheap with a passive RC filter ($22k\Omega$, $68nF$, yielding a cutoff frequency of $106Hz$), but there's a big caveat here! From the SSM2164 datasheet, the CV inputs of the SSM2164 are connected to a $4.5k\Omega$ / 500Ω resistor divider. With the RC filter in place adding some impedance at the input, the v_q that the SSM2164 will "see" is only $\rho = \frac{0.5+4.5}{0.5+4.5+22}$ of the CV output by the Shruthi-1 digital board. The new expression for Q is thus $\frac{1}{2}10^{\frac{3}{2}\rho v_q}$.

So much to save a pair of op-amps! We would have loved using a smaller R to avoid adding to the input impedance of the SSM2164 control inputs, but then the capacitor would have been too large to fit on the board.

2.3 Pushing self-oscillation

Self-oscillation occurs when there is no feedback from the BP node to the input of the circuit. Unfortunately, this cannot occur with the circuit of section 1 since it is not possible to entirely mute the SSM2164 gain cell controlling resonance. With the Shruthi-1 Q CV set to a maximum value of $5V$, we get a Q of only $\frac{1}{2}10^{\rho\frac{3}{2}\times 5} = 12.2$. Still not there! Self oscillation would happen if the signal fed back from the BP node to the input of the filter was null ; but a small portion of it "bleeds" through the feedback gain cell which is not entirely closed. We can cheat and compensate this bleed by always feeding back a small fraction of the BP node to the input, through a R_O resistor. In this case, the expression for Q becomes:

$$Q = \frac{1}{2}\left(10^{-\frac{3}{2}\rho v_q} - \frac{R_Q}{R_O}\right)^{-1}$$

It is now possible to reach self-oscillation even if the feedback gain cell is bleeding a bit. The value of R_O is chosen so that Q can reach 0 before v_q reaches $5V$. We observed a compensation of the bleed with values of R_O lower than $680k\Omega$, and picked $R_O = 220k\Omega$ to be on the safe side, even if this means a less gentle "landing" towards self oscillation.

2.4 Soft clipping

Once self-oscillation is reached, the bad surprise is that it crashes on the op-amp rails, yielding a very squelchy sound. Adding a pair of head-to-head Zeners across the BP integrator capacitor ensures that the self-oscillation signal will be soft-limited. We found that a Zener voltage of 4.7V gave the best results with TL07x op-amps (which crash at $\pm 3.6V$ when powered by $\pm 5V$).