Application Note 2

Analog Audio Parametric Equalizer

Highlights
Pot and Switch Components
Target Optimizer for Curve Parameters
Potentiometer Analysis
Noise Analysis
LEQ, HEQ, BEQ Filters

Design Objective
Parametric Equalizer: Lowpass Shelving or Bell
Cut/Boost: ±15dB
Frequency: 30Hz - 300Hz
Bell Octave: 0.33 - 3.0

Parametric Equalizer: Highpass Shelving or Bell
Cut/Boost: ±15dB
Frequency: 1k6Hz - 16kHz
Bell Octave: 0.33 - 3.0

Parametric equalizers allow for all of the parameters of an equalization filter to be adjusted independently. Typically this includes three parameters: cut/boost gain (dB), frequency (Hz), and Width (Octave) for bell/Bandpass equalizers. This type of control is often used in professional audio equipment where more sophisticated and powerful equalization is demanded.

There are three forms of equalization configurations: Lowpass Shelving, Highpass Shelving, and Bandpass Bell. In FilterShop these are known as LEQ, HEQ, and BEQ respectively.

In many cases each parametric band is setup to provide both shelving or bell curve equalization, by a selection switch. The shelving can be either Lowpass or Highpass. Generally low frequency (Bass) filters use Lowpass Shelving, and high frequency (Treble) filters use Highpass Shelving.

For our example here, two different parametric filters will be constructed: one for low frequencies (LEQ/BEQ), and one for high frequencies (HEQ/BEQ).
To help visualize a typical implementation of these kinds of equalizers, note the physical panel layouts shown above. Here the two parametric bands are shown. Note that the shelving type is different for the two bands. A switch is used to select either shelving or bell, and three pots are used for cut/boost, frequency, and Q. The Q is given in Octaves, and the control is only active when the Bell mode is selected.

**Scale Setup**

Since we are working in the audio frequency range, a 20Hz-20kHz frequency range would seem appropriate. A Log axis will be used, and an initial magnitude scale of 3dB/Div with 12 major divisions on the Magnitude graph. This will provide a ±18dB vertical scale range.

**Target Setup**

There are three different types of target filter TFBs involved: LEQ, BEQ, and HEQ. We shall start by setting the Ao dB values to 15.0 (our maximum boost), and set the initial Q of the BEQ to 1.0. Each of these are setup in different TFB locations as shown below.

However, each TFB is actually only turned on one at a time. For the frequencies, the LEQ and BEQ are set to 300Hz and the HEQ is set to 1600Hz. None of these are critical values, but merely starting values to display the shape of these curves.
The Magnitude graph above shows the three curves of each TFB. The Blue curve is LEQ, Green is BEQ, and Red is HEQ. These curves represent the maximum boost position of +15dB.

**EQ Topology Selection**

A basic equalization topology must now be chosen.

There are several different types of cut/boost circuits. Each has advantages/disadvantages depending on the requirements of the equalizer.

Since these equalizers will produce multiple types of filter functions, it is best to start with one of the generic Multipass style equalizer circuits. We will choose the MEQ_1.

This will allow us to design the more complex inner filter as a separate entity.
The MEQ_1 circuit is shown here. Note that a transfer function block (H1) is used to represent the actual filter function. This is useful since our equalizers will need to employ Lowpass, Highpass, and Bandpass filter functions.

The circuit is very simple, and has only three resistors, the cut/boost pot, in addition to H1.

Running *Synthesis* on this circuit simply designs the resistor values for us based on the required maximum cut/boost, and sets up the required parameter values for H1. All we are really after right now is the three resistor values. We could use any of our three target TFBs for this, since they all require the same 15dB range. We choose to activate the BEQ TFB.

When *Synthesis* is run, it prompts for preset values for R1 and P1. For these values, 5.11k and 10k are chosen. The resulting circuit is shown here. To produce the 15dB cut/boost range, R2 must be 1.10k based on R2=R3=5.11k.

Note that H1 now contains the text "BP1". If you open the component editor for H1 you will see the parameters that have been defined.

A BP1 was setup with Fo=300Hz, and Q=1.0. The gain Ao is also set to unity.
If you now view the Magnitude graph, you will see a flat line at 0dB. This is because the Pot’s wiper position is at 50% - center. To see the circuit’s response with maximum boost, double click on the Pot and change the position to CW, or full clockwise. Then recalculate the circuit. The response is shown above.

Not too surprising, the response is the same as the original BEQ target. You can change the Pot wiper position to any other values and observe the response at different rotations.

**Determining Q Value Range**
The specification for the BEQ peaking width value is to range from 1/3 octave to 3 octaves wide. We need to determine what Q values these limits represent. An easy way to get this information is from the Target | Analog Filters | Allpole dialog.

Open the dialog, and then make sure that either the Bandpass or Bandreject transformation option is selected. This is necessary to enable the Total Q field. All other fields are unimportant. Note the small button inside the editing field. Click this [...] button.
Another small dialog will open with three other editing fields. This dialog allows you to specify Q by edge frequencies or octave width.

We can enter an octave width value here, and then the equivalent Q value will be calculated.

For our first limit value of 1/3 octave, we enter 0.333.

After clicking Ok, the Total Q value is then calculated as 4.32.

For our other limit value of 3 octaves, we enter 3.0.

The resulting Q value is 0.404.

We now know our Q range for the BEQ filter design: **0.4 to 4.3**
H1 Circuit Topology Selection

For the BEQ configuration, the generic H1 transfer function block must be a 1st order Bandpass BP1 filter. For the LEQ configuration, H1 is an LP1 filter, and for the HEQ configuration H1 will need to be an HP1 filter.

We will need to choose a filter circuit to implement H1 which can produce all of these different types of transfer functions. Furthermore, we wish to be able to control all of the parameters independently without interaction.

A state variable type topology is up to the task. Since the BP1 filter is actually a 2nd order polynomial transfer function, we need a 2nd order state variable. The LP1 and HP1 functions are 1st order, but these can be obtained from a degenerated form of a 2nd order circuit.

There are many different state variable filters in the Synthesis catalog. One of the best ones which produces full independent parameter control, in addition to true parameter linearity is the MP2_SV1 topology.
This circuit has additional components for producing Allpass and Bandreject outputs. We will not need these outputs for equalizers, so only the four opamps in the upper area of the circuit will actually end up being used.

### Frequency and Q Controls

The selection of which resistors will be replaced with Pots to control the F/Q parameters is now shown below. Since we have a 2nd order function, one would expect that two resistors must be changed for the Frequency parameter. In this case, R3 and R4 are used for Frequency, and have identical values.

For Q, some circuits only require a single resistor to be changed. However for this circuit we will need to change two resistors to maintain constant gain at the Bandpass output. R2 and R8 provide the Q control, and again will have identical values.

The specification calls for a frequency parameter range of about 10:1. The Q values range from 0.4 to 4.3 which is just over 10:1. We will choose to use a Pot of 10k with a series resistor of 1.1k. This creates a variable resistance from 1.1k - 11.1k, which yields the 10:1 resistance ratio requirement.
Before we start Synthesis, the Target system will be setup with a single TFB using a BP1 filter, $A_o=0\text{dB}$, $F_o=300\text{Hz}$ and $Q=4.3$. This represents the required parameters for the low frequency parametric band, with both the $F$ and $Q$ control set to minimum resistance. In the circuit, we change the precision of the capacitors to 20%, to keep the values limited.

When Synthesis is started, preset values are requested for $R_3$ and $R_1$. $R_3$ is one of the frequency controls, and at $300\text{Hz}$ the value is 1.1K. For the input resistor $R_1$ we will try 5.11K. The resulting circuit is shown below.

![Circuit Diagram]

The $R_2, R_8$ values are 1.18K. These will be replaced by Pots and since we will keep the resistance range for the $Q$ Pots the same as the $F$ Pots, they will be 1.1K. This will result in a slightly different $Q$ range, but this is not a critical parameter for most equalizers, and will be acceptable for this example.

The remaining values are all 5.11k. We can now change the circuit to Custom, and start editing the circuit to include the pots, and remove the unneeded Allpass/Bandreject sections. After the editing is complete, the circuit on the following page is produced.
The only output we are interested in is the Bandpass output (BP1). All other outputs have been removed. All four of the pots are connected in variable resistance configuration, meaning that one end is shorted to the wiper.

Note that the F pots have the CCW end connected to the wiper, while the Q pots have their CW end connected to the wiper. This is determined by which rotation direction must be minimum resistance. In the case of F, the minimum resistance needs to be at the CW end, which corresponds to the highest frequency. In the case for Q, the minimum resistance is needed in the CCW position which corresponds to highest Q, or the 1/3 octave position. Each of the F and Q controls would be dual ganged units.

**Frequency Control Taper Selection**

We can now begin the process of determining the best taper for the frequency control. The frequency control consists of the two pots P1/P2. They currently have ideal linear taper. To see how the center frequency changes under rotation with the current taper, we use the Processing | Potentiometer Analysis dialog.

We enable the P1,P2 entries since they are a ganged unit and need to be rotated together, and enter 11 steps for rotation. The circuit BP1 output is selected.
The results are shown above. The center frequency ranges from 30Hz to 300Hz. Note that the curves are more dense at the low frequency end. Ideally we wish to have an even density across the rotation. Clearly a linear taper is not best.

Since the minimum resistance value occurs at the CW position of the frequency control, a reverse log style taper is the logical choice. There are several taper libraries in the system, and here will load the Noble library which offers many different tapers.

One obvious measure of determining proper taper is to first check that the correct center frequency is produced. In other words, since our frequency range is 30Hz-300Hz, the center frequency should be the geometric (log) mean value between those ends. This can be easily calculated as: sqrt(30*300) = 95Hz.

Looking at the Red curve above, which is the center 50% rotation position, we see that the center frequency is 55Hz. This is a substantial error from the desired 95Hz, and again confirms that the curves are crammed in the lower frequency end of the rotation. We will now try a reverse log taper.
The tapers must be changed on both the P1/P2 pots. Double click on one of the controls. The C taper class is reverse log. Each C taper is given with a number indicating the percentage value at center position. The 15% value generally represent standard Log/RevLog style tapers.

We will start with the NR-C15. Load this taper for this pot, and then repeat again for the other frequency pot. When completed, run the Potentiometer Analysis again.

The results are shown below. We now see that the curves are more dense in the upper frequency range, and the center is now at 130Hz. The previous test was too low, but this is now too high. We need less log curvature and more linearity in the taper shape.

Again change the tapers on both controls, but this time load the NR-C25 taper.
When done, rerun the Potentiometer Analysis again. As shown above, the C25 taper is now perfect. The center frequency is almost exactly 95Hz, and the curve density is evenly distributed.

### Q Control Taper Selection

The Q parameter behaves similar to frequency, meaning that a geometric mean should be produced in the center. Since the end values are about 0.43 and 4.3, the center Q should be: \( \sqrt{0.43 \times 4.3} = 1.36 \)

The maximum Q value occurs at the CCW rotation, so these controls require Log style taper. Since the same 10:1 range is used like the frequency controls, a good guess for the required taper would be the A25 type. This is the same 25% resistance value at center, but with the A Log configuration.

Change both of the P3/P4 pots to the NR-A25 taper, and then run Potentiometer Analysis again. However, this time the P1/P2 controls are disabled for rotation, and the P3/P4 controls are enabled. We are rotating the Q pots.

The magnitude graph on the following page displays the Q rotation results. The curves appear very evenly distributed. However, we have no direct means of reading out the actual Q value produced by the circuit at the center position.
Measuring the Actual Circuit Q

A neat trick to determine the circuit Q is to use the Target | Optimizer to adjust the parameters of the BP1 TFB to match the shape of the actual curve. Since the BP1 target is already setup in the Target Parameters, and the 50% rotation curve is already in the Guide Curve array, everything is ready to go.

Open the Target | Optimizer and choose the 50% position Guide Curve. Select all three parameters for optimization, using Peak Error and the full frequency range. Click the Run button.

The circuit Q parameter is: 1.42

Easy! This is very near our desired center Q of 1.36. In fact we can now measure the Q at the limits of rotation by simply choosing the 0% and then the 100% Guide Curves for optimization. The Q values are 0.45 and 4.6. The ideal median value based on these actual limits is: 1.43
Deriving the LP1 Configuration

To support the LEQ equalizer mode, we now must modify the Bandpass circuit to produce a Lowpass output. We wish to produce this function using only a single pole or double pole switch. We could simply switch to another dedicated LP1 circuit, but this would require another section for the frequency control. The most efficient method is to create the LP1 function from the 2nd order state variable. It is also best if we can maintain the output at the same BP1 location.

Using a two pole switch, we can short out C2 and switch out the P4 Q Pot to a fixed resistor. Since the U3 output is then zero, the other Q Pot P3 will have no effect on the response.

The fixed resistor R9 must be 5.11k to produce the correct frequency values. The graph below shows the response.
**Deriving the HP1 Configuration**

To support the HEQ equalizer mode, we now must modify the Bandpass circuit to produce a Highpass output. Again, we wish to produce this function using only a single pole or double pole switch. Using a two pole switch, we can open C1 and switch out the P3 Q Pot to a fixed resistor. The remaining Q Pot section P4 then controls the open loop gain within a feedback loop. Changes in the Q control rotation will have no effect on the HP1 response.

The fixed resistor R9 must be 5.11k to produce the correct frequency values. Also, the HP1 response covers the 1k6k-16kHz range, C2 is changed from 470n to 8.2n. The graph below shows the response.

Since we have three opamps now inside a feedback loop, some additional compensation will be required. This will be addressed in the final circuit.
BEQ/LEQ Equalizer Configuration

We can now add our BP1/LP1 filter circuit to the cut/boost stage to produce the BEQ/LEQ equalizer. The circuit shown below also now contains the switch components to select the BEQ or LEQ modes.

Note that the S1 switch configuration shorts out either the R11 resistor, or the P4/R2 pair. This ensures that a feedback connection is always maintained around the opamp U1 even during switch transitions, where neither position is connected.

The cut/boost gain control is a single potentiometer. But, since we are already using dual controls for the F,Q parameters we might consider the advantages of using a dual control for gain as well.

If the gain control is in the center position (0dB) the equalizer response is simply a flat line. There is no signal supplied to the filter section input. However, the output of the filter section (BP1/LP1) is constantly being fed into the gain stage U3 through R9. There is always a gain of 13dB on the BP1/LP1 filter output. The noise of the filter circuit is being amplified by nearly the maximum gain of the equalizer, even when the equalizer is doing nothing at 0dB center.
The noise situation can be improved by using another gain Pot at the output of filter circuit, in addition to the input gain Pot. Since the gain increases/decreases in both directions from center, a special arrangement is required.

As shown above, the new gain Pot P5 has both ends tied together. In the center position the resistance through the Pot is 2.5k. As the control is rotated towards either end, the resistance decreases to zero. Thus the gain applied to the filter circuit is minimum in the center and maximum at either end.

The total gain applied to the filter section noise is now only 3dB, when the gain Pot is in the center position. This is a 10dB noise reduction from the previous configuration.

Therefore, the advantage of using a dual control for the gain parameter is a significant reduction in overall noise, when the control is not at maximum cut or boost.
Gain Control Taper Selection

We now run the Potentiometer Analysis rotating the P5,P6 controls to analyze the cut/boost gain curves using default ideal linear tapers.

With 11 steps across the rotation, the ideal increments should be exactly 3dB. Here we see that the curves are crowded near zero. This means that the gain control has little effective change near the center, and most of its change near the ends of the range.

We cannot use Log or RevLog type tapers for this case, since the control requires symmetrical change from center. The solution is the S tapers. S tapers have symmetrical curvature, always with a center ratio of 50%.

The S tapers are sometimes known as W or B tapers, depending on the manufacturer. In the case of Noble, they are B tapers.

The best configuration for this circuit turned out to be a mix of two different B tapers: the standard B for P5 and the 3B for P6.
The Magnitude graph above shows the final result with the B/3B taper combination. It should be noted that many other taper/circuit solutions are also possible. By adding additional resistors around the pots or as loads on the wipers of the pots, an infinite number of different curve families are possible.

The noise density for the same family of gain curves is shown here, using the RC5534 opamp.

Using the Processing | Noise Analysis dialog, the broadband noise is -108dBm in the center 0dB gain position.

The graphs on the following page show the LEQ response profiles.
**BEQ/HEQ Equalizer Configuration**

We can now add our BP1/HP1 filter circuit to the cut/boost stage to produce the BEQ/HEQ equalizer. The circuit shown below also now contains the switch components to select the BEQ or HEQ modes.

Note that the S1 switch configuration shorts out either the R11 resistor, or the P3/R7 pair. This ensures that a feedback connection is always maintained around the circuit even during switch transitions, where neither position is connected.

We can reuse the gain control configuration developed in the previous BEQ/LEQ circuit.

The following page shows the BEQ gain family, along with the Noise Density for the same family of curves. The broadband noise is -105dBm at the center gain position of 0dB.

The following page shows the HEQ gain family and frequency family of rotation curves.
BEQ/HEQ Compensation

As previously mentioned, additional compensation circuitry is needed for this BEQ/HEQ configuration. When the HEQ mode is in operation, C1 is opened and the loop gain increases. Phase delay through the network will cause the feedback to become positive at high frequencies, with gain greater than unity. Due to the Pots, the stability condition can vary greatly depending on their positions.

The worst case stability condition can be defined as follows:

1. Max feedback occurs when the gain control is full CCW.
2. Max delay (lag) occurs when the frequency control is CCW.
3. Max loop bandwidth occurs when the Q control is CCW.

Using these conditions, the scale frequency range was increased to 20MHz, and the analysis run again. The results are shown here.

It is clear that the response becomes erratic near 2.5MHz, with sharp peaks present.

To stabilize the circuit, we will add phase lead compensation at two locations. This will reduce the phase shift and prevent the potential of oscillations.
The modified circuit below now has two additional capacitors: C3 and C4. These two caps shunt high frequencies around R11 and R12 and provide the desired phase lead at high frequencies.

The 47p values for C3 and C4 were arrived at by trial and error, based on the smoothest result in the 2-3MHz region.

The graph below shows the same analysis conditions as before, but now with the compensation caps included.

The sharp peaks in the 2-3MHz region have been eliminated.

This completes the BEQ/LEQ and BEQ/HEQ parametric equalizer designs.