RaneNote 122

OPERATOR ADJUSTABLE EQUALIZERS: AN OVERVIEW

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INTRODUCTION

This paper presents an overview of operator adjustable equalizers in the professional audio industry. The term "operator adjustable equalizers" is no doubt a bit vague and cumbersome. For this, the author apologizes. Needed was a term to differentiate between fixed equalizers and variable equalizers.

Fixed equalizers, such as pre-emphasis and de-emphasis circuits, phono RIAA and tape NAB circuits, and others, are subject matter unto themselves, but not the concern of this survey. Variable equalizers, however, such as graphics and parametrics are very much the subject of this paper, hence the term, "operator adjustable equalizers." That is what they are—equalizers adjustable by operators—as opposed to built-in, non-adjustable, fixed circuits.

Without belaboring the point too much, it is important in the beginning to clarify and use precise terminology. Much confusion surrounds users of variable equalizers due to poorly understood terminology.

What types of variable equalizers exist? Why so many? Which one is best? What type of circuits prevail? What kind of filters? Who makes what? Hopefully, the answers lie within these pages, but first, a little history.

A LITTLE HISTORY

No really big histories exist regarding variable equalizer use. Good short histories appear in [1]-[3]. An expanded short history follows.

Hurrah for Hollywood. Mother Nature and Hollywood spawned the first use of variable equalizers for sound improvement. Motion pictures with sound brought audio playback systems into theaters for the first time. Soon, some people's attention focused on just how bad these reproduction systems sounded. John Volkman was one of these people. It was the '30s and Volkman worked for RCA. Credit John with being the first person to use a variable equalizer to improve reproduced sound. He applied this new tool to equalize a motion picture theater playback system.

While Bell Labs used fixed equalizers earlier than this for correcting audio transmission losses [4], Volkman represents one of the first uses of an external variable equalizer as an added component to an installed system. Telephone applications involved integrating equalization as part of the receiving electronics, as opposed to thinking of the equalizer as a separate entity.

During the same period Volkman experimented with equalizers for reproduced sound, Hollywood found uses for them in producing sound. Langevin, Cinema Engineering, and others [4], created outboard operator adjustable equalizers for post-production sound effects and speech enhancement. Langevin Model EQ-251A represents very early use of slide controls. While not a graphic equalizer in today's sense, it was the forerunner. The EQ-251A featured two slide controls, each with switched frequency points. One slider controlled a bass shelving network with two corner frequency choices, while the other provided peaking boost/cut with four switchable center frequencies. This passive unit looked and performed equal to anything manufactured today.

Art Davis's company, Cinema Engineering, developed the first recognizable graphic equalizer [4]. Known as the type 7080 Graphic Equalizer, it featured 6 bands with boost/cut range of 8 dB, adjustable in 1 dB steps. (After Art Davis moved to Altec, he designed a 7 band successor to the 7080 known as the Model 9062A. A hugely successful graphic equalizer selling into the '70s.) Being an active design, the 7080 allowed signal boosting without loss—a nice feature. (With passive units, boosting of signals requires an initial broad band signal loss and then reducing the loss on a band-by-band basis. For example, flat might represent 16 dB loss while a 6 dB boost represented only 10 dB loss. It was all a matter of reference point.)

Another innovative feature of the 7080 was the first use of staggered mixing amps to aid in smooth combining of the equalized audio signal. Cinema Engineering designed 3 mixing amplifiers for 6 bands. Using this approach, no amplifier mixed adjacent bands. The center frequencies were 80Hz, 200Hz, 500Hz, 1.25kHz (labeled 1.3kHz), 3.2kHz (labeled 3kHz), and 8kHz. The amplifiers mixed 80Hz + 1250Hz, 200Hz + 3200Hz, and 500Hz + 8kHz respectively. Using separate amplifiers to mix signals spaced 4 octaves apart, resulted in seamless recombination at the output. (Later Art Davis would use a similar technique in the design of the first Altec-Lansing active graphic equalizers.)

Not much happened during the '40s and early '50s due to World War II and its aftermath. Most applications of variable equalizers involved post-production work. No serious success at room equalization is known. Then in 1958, Wayne Rudmose (a professor at Southern Methodist University, Dallas, Texas) successfully applied new theories about acoustic equalization to the Dallas Love Field Airport. Dr. Rudmose published his monumental work [5] and sound system equalization was born.

In 1962, Texas made another major contribution to variable equalizer history. This time it was the University of Texas (Austin) and a physics professor named C.P. Boner. Dr.s Boner and Rudmose were contemporaries and friends, having co-authored a paper 23 years earlier [6] . Boner, acknowledged by many, as the father of acoustical equalization, built organs as a hobby. From his organ/room tuning experiences and acoustical physics knowledge grew a profoundly simple theory. Boner reasoned that when feedback occurs, it did so at one precise frequency, and to stop it all you had to do was install a very narrow notch filter at that frequency. He went to one of his former students whose company made precision filters for instrumentation and asked him to design a narrow band audio filter. Gifford White agreed, and launched White Instruments into the new field of acoustic equalization.

Armed with White equalizers, Boner established the foundation theory for acoustic feedback, room-ring modes, and room-sound system equalizing techniques [7]-[10]. Expanding Boner's work was a student of Wayne Rudmose named William Conner. In 1967, Conner published a concise paper [11] still considered among the best to describe the theory and methodology of sound system equalization.

Also in 1967, Art Davis, along with Jim Noble and Don Davis (not related) developed the industry's first 1/3-octave variable notch filter set (passive) for Altec-Lansing. Don Davis presented the paper to the Audio Engineering Society in October, 1967 [12]. Dubbed the “Acousta-Voice” system, it ushered in the modern age of sound system equalization and represented the ultimate in speed and convenience. The Acousta-Voice system proved another path existed for the control of room-ring modes. As an alternative to Boner's narrow-band notching technique, 1/3-octave “broad-band” filters produced the same results.

The rest, as they say, is history. A 20 year history that witnessed an explosion of variable equalizer developments. Among the most noteworthy being the 1/3-octave graphic equalizer, the parametric equalizer, use of integrated circuits, development of the gyrator (synthetic inductor), active LC and RC designs, development of constant-Q (bandwidth) graphic equalizers, and the application of microprocessors for control and memory. All of these developments, in this author's opinion, fall into the category of improvements—albeit, very important improvements—rather than qualifying as new concepts applied to variable equalizers. Recently, however, two categorically new concepts appeared.

The first is transversal equalizers: In 1984, Industrial Research Products introduced the first variable equalizer based on analog transversal filter technology [13] (more on transversal filters later).

The second is digital equalizers: In 1987, Yamaha introduced the DEQ7 Digital Equalizer, the first stand-alone variable equalizer based on digital signal processor (DSP) technology [14]. A combination "graphic" (bad terminology since there is no graphical representation of settings) and parametric, the DEQ7 featured 30 different built-in configurations. Also in 1987, Roland previewed a digital parametric equalizer [15], the first variable equalizer to include the new digital audio transmission standard developed by the Audio Engineering Society [16].

CHOICES, CHOICES, CHOICES

Figure 1 shows the breadth of operator adjustable equalizers. And this covers only the manually adjustable analog units—microprocessor-controlled and full-digital designs are omitted. Such are your choices as a user.

Estimates suggest only 25% of the equalizers sold find their way into serious permanent sound systems. Uses for the remaining 75%, split between program enhancement and sound reinforcement.

Program enhancement primarily appears in live performance, recording studio, broadcast, and post-production marketplaces. Within these markets equalizers do everything from simple band limiting to complex sound manipulation.

Sound reinforcement uses equalizers everywhere from small lounge acts to large touring companies. Most applications are for compensating ragged loudspeaker power responses rather than attempting any sort of serious room equalization. This is true for monitor loudspeaker systems as well as mains. Yet, the equalizer is the crucial link in vastly improving the system's sound.

With such diverse applications it is not surprising to find so many choices. To understand the choices, however, is first to understand the terminology.

TERMINOLOGY

Equalizer terminology deserves better positioning than the back of the book. So instead of a complete glossary at the end, an abbreviated glossary appears now. To confuse and make sure you are paying attention, this will not be in alphabetical order. Hopefully, appearing in order of importance for understanding equalizers.

Passive Equalizer. A variable equalizer requiring no power to operate. Consisting only of passive components (inductors, capacitors and resistors) passive equalizers have no AC line cord. Favored for their low noise performance (no active components to generate noise), high dynamic range (no active power supplies to limit voltage swing), extremely good reliability (passive components rarely break), and lack of RFI interference (no semiconductors to detect radio frequencies).

Disliked for their cost (inductors are expensive), size (and bulky), weight (and heavy), hum susceptibility (and need careful shielding), and signal loss characteristic (passive equalizers always reduce the signal). Also inductors saturate easily with large low frequency signals, causing distortion. Used primarily for notching in permanent sound systems.

Active Equalizer. A variable equalizer requiring power to operate. Available in many different configurations and designs. Favored for low cost, small size, light weight, loading indifference, good isolation (high input and low output impedances), gain availability (signal boosting possible), and line-driving ability.

Disliked for increased noise performance, limited dynamic range, reduced reliability, and RFI susceptibility. Used everywhere.

Graphic Equalizer. A multi-band variable equalizer using slide controls as the amplitude adjustable elements. Named for the positions of the sliders "graphing" the resulting frequency response of the equalizer. Only found on active designs. Both center frequency and bandwidth are fixed for each band.

Rotary Equalizer. A multi-band variable equalizer using rotary controls as the amplitude adjustable elements. Both active and passive designs exist with rotary controls. Center frequency and bandwidth are fixed for each band.

Parametric Equalizer. A multi-band variable equalizer offering control of all the "parameters" of the internal bandpass filter sections. These parameters being amplitude, center frequency and bandwidth. This allows the user to not only control the amplitude of each band, but also to shift the center frequency and widen or narrow the affected area. Available with rotary and slide controls.

Sub-categories of parametric equalizers exist for units allowing control of center frequency but not bandwidth. For rotary control units the most used term is quasi-parametric. For units with slide controls the popular term is para-graphic. The frequency control may be continuously variable or switch selectable in steps.

Cut-only parametric equalizers (with adjustable bandwidth or not) are called notch equalizers, or band-reject equalizers.

Transversal Equalizer. A multi-band variable equalizer using a tapped time delay line as the frequency selective element, as opposed to bandpass filters built from inductors (real or synthetic) and capacitors. The term "transversal filter" does not mean "digital filter." It is the entire family of filter functions done by means of a tapped delay line. There exists a class of digital filters realized as transversal filters, using a shift register rather than an analog delay line, the inputs being numbers rather than analog functions. To date, however, due to expensive hardware, digital transversal filter realization of variable equalizers remains in the laboratory. The only available transversal equalizers today are from Industrial Research Products [13], employing all-pass analog filters for the tapped delay line.

Cut-Only Equalizer. Term used to describe graphic equalizers designed only for attenuation. (Also referred to as notch equalizers, or band-reject equalizers). Usually applied to active designs. The flat (0 dB) position locates all sliders at the top of the front panel. Comprised only of notch filters (normally spaced at 1/3-octave intervals), all controls start at 0 dB and reduce the signal on a band-by-band basis. Used only in permanent sound systems. Proponents of cut-only philosophy argue that boosting runs the risk of reducing system headroom.

Boost/Cut Equalizer. The most common graphic equalizer. Available with 10 to 31 bands on octave to 1/3-octave spacing. The flat (0 dB) position locates all sliders at the center of the front panel. Comprised of bandpass filters, all

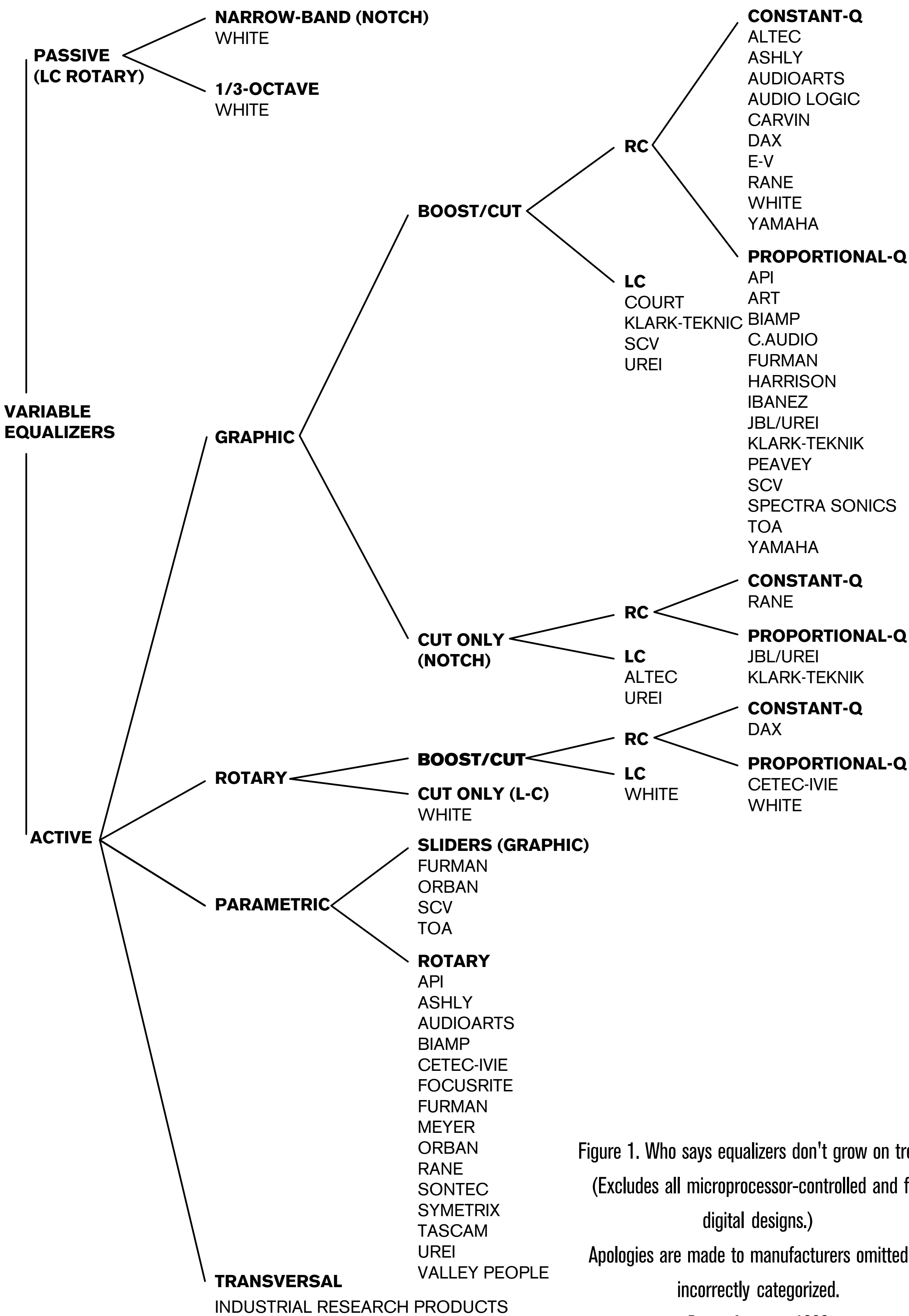

Figure 1. Who says equalizers don't grow on trees? (Excludes all microprocessor-controlled and full digital designs.)
Apologies are made to manufacturers omitted or incorrectly categorized.
Date of survey-1988

controls start at their center 0 dB position and boost (amplify or make larger) signals by raising the sliders, or cut (attenuate or make smaller) the signal by lowering the sliders on a band-by-band basis. Commonly provide a center-detent feature identifying the 0 dB position. Used by all branches of the professional audio industry. Boost capability necessary for all forms of program equalization. Proponents of boosting in permanent sound systems argue that cut-only use requires make-up gain which runs the same risk of reducing system headroom.

Narrow-Band Filter. Term popularized by C.P. Boner to describe his patented (tapped toroidal Inductor) passive notch filters. Boner's filters were very high Q (around 200) and extremely narrow (5 Hz at the -3 dB points). Boner used large numbers (around 100-150) of these sections in series to reduce feedback modes [9].

Today's usage extends this terminology to include all filters narrower than 1/3-octave. This includes parametrics, notch filter sets, and certain cut-only variable equalizer designs.

1/3-Octave. Term used to describe variable equalizers with the bands located on standard ISO (International Organization for Standardization) recommended 1/3-octave center spacing.

Generally for boost/cut equalizers, not only are the filters located on 1/3-octave spacing but they are also 1/3-octave wide, measured at the -3 dB points referenced from the maximum boost or cut point (symmetrical boost/cut responses assumed). Fig. 2 diagrams this reference point.

Cut-only (notch or band-reject) equalizers unfortunately offer no such standardization on bandwidth measurement points. If referenced as being 1/3-octave wide, you will find two schools of thought as illustrated by Fig. 3. One manufacturer may use the same definition as given above for boost/cut designs while another uses a new definition. The new definition measures the -3 dB points from the 0 dB reference line. Applications exist for both approaches. Some permanent sound system installations require the narrower design while other applications need the wider response. The narrower response is more selective, but less efficient. There are also many variations between these two extremes.

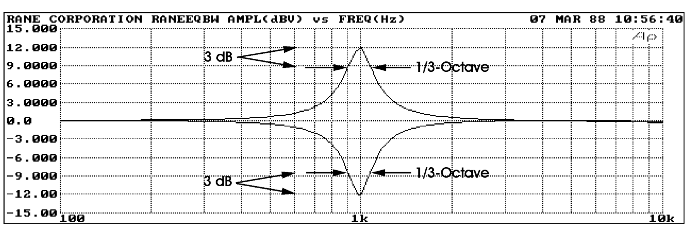

Figure 2. Symmetrical boost/cut response showing 1/3-octave bandwidth.

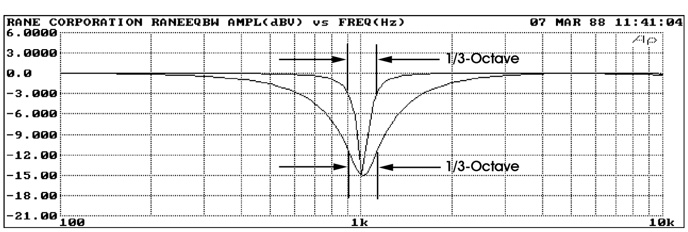

Figure 3. Cut-only (notch or band-reject) response showing different 1/3-octave measurement points.

LC Filter (Also LCR, LRC, etc.). Passive filter comprised of capacitors (C), resistors (R), and inductors (electronic symbol "L"; why "L?" Well, you see they couldn't use "I" because that was being used for current). Note that both active and passive equalizers use LC filters. In active units, the actual filter element is passive; the active elements act as buffers, mixers and gain blocks.

RC Filter. Active filter made from resistors (R), capacitors (C) and an amplifier (either tubes, transistors, or integrated circuits).

Two main categories exist. The first uses active RC networks to synthesize inductors (gyrators) and then create bandpass or band-reject filters based on original LC designs. The second uses active RC networks s directly to create bandpass or band-reject filters.

Q (Bandwidth). The quality factor, or "Q," of a filter is an inverse measure of the bandwidth. To calculate Q, divide the center frequency by the bandwidth measured at the-3 dB (half-power) points. For example, a filter centered at 1 kHz that is 1/3-octave wide has -3 dB frequencies located at 891 Hz and 1123 Hz respectively, yielding a bandwidth of 232 Hz (1123-891). The quality factor, Q, is therefore 1 kHz divided by 232 Hz, or 4.31.

Going the other way is a bit sticky. If Q is known and the bandwidth (expressed in octaves) is desired, direct calculation is not obvious—nor easy. Development of a direct expression appears in [17], along with a hand-held calculator program to make this easier.

Proportional-Q Equalizer (also Variable-Q). Term applied to graphic and rotary equalizers describing bandwidth behavior as a function of boost/cut levels. Paul Wolff of API recommends the term "proportional-Q" as being more accurate and less ambiguous than "variable-Q." If nothing else, "variable-Q" suggests the unit allows the user to vary (set) the Q, when no such controls exist.

Fig. 4 shows proportional-Q response for 4 different boost settings. The bandwidth varies inversely proportional to boost (or cut) amounts, being very wide for small boost/cut levels and becoming very narrow for large boost/cut levels. The skirts, however, remain constant for all boost/cut levels. Compare with Fig. 5.

Constant-Q Equalizer (also Constant-Bandwidth). Term applied to graphic and rotary equalizers describing bandwidth behavior as a function of boost/cut levels. Since Q and bandwidth are inverse sides of the same coin, the terms are fully interchange-able.

Fig. 5 shows constant-Q response for 4 different boost settings. The bandwidth remains constant for all boost/cut levels. For constant-Q designs, the skirts vary directly proportional to boost/cut amounts. Small boost/cut levels produce narrow skirts and large boost/cut levels produce wide skirts.

Equalize/Attenuate. Original terms used by Art Davis to signify direction of equalization. Equalize meant to make bigger and attenuate meant, of course, to make smaller. Replaced today by boost/cut terminology.

Lift/Dip. Popular European term meaning boost/cut.

Peaking Response. Term used to describe a bandpass shape when applied to program equalization. Fig. 2 shows a peaking response.

Shelving Response. Term used to describe a flat (or shelf) end-band shape when applied to program equalization. Fig. 6 shows shelving responses. Also known as bass and treble tone control response. Ambiguities exist when describing shelving equalization controls regarding corner frequencies. Fig. 6 shows the two conflicting definition points. Comer frequency 1 represents the normal engineering definition of the ±3 dB point. Corner frequency 2, however, represents a definition point more relevant to the user. Normally a user wants to know the available boost/cut amount at the top or bottom of the shelving response.

Symmetrical (Reciprocal) Response. Term used to describe the comparative shapes of the boost/cut curves for variable equalizers. Fig. 2 shows symmetrical or reciprocal responses.

Asymmetrical (Non-reciprocal) Response. Term used to describe the comparative shapes of the boost/cut curves for variable equalizers. Fig. 7 shows asymmetrical or non-reciprocal responses.

Gyrator Filters. Term used to describe a class of active filters using gyrator networks. Gyrator is the name given for RC networks that mimic inductors. A gyrator is a form of artificial inductor where an RC filter synthesizes inductive characteristics. Used to replace real inductors in filter design.

Discrete Equalizer. A variable equalizer comprised solely of separate (discrete) transistors, as opposed to designs using integrated circuits. Currently, it is believed only API makes discrete equalizers.

Combining (Interpolating) Equalizer. Term used to describe the summing response of adjacent bands of variable equalizers. If two adjacent bands, when summed together, produce a smooth response without a dip in the center, they are said to combine well.

Good combining or interpolating characteristics come from designs that buffer adjacent bands before summing, i.e., they use multiple summing circuits. If only one summing circuit exists for all bands, then the combined output exhibits ripple between center frequencies.

Altec-Lansing first described Art Davis's buffered designs as combining, and the terminology became commonplace. Describing how well adjacent bands combine is good terminology. However, some variations of this term confuse people. The phrase "combining filter" is a misnomer, since what is meant is not a filter at all, but rather whether adjacent bands are buffered before summing. The other side of this misnomered coin finds the phrase "non-combining filter." Again, no filter is involved in what is meant. Dropping the word "filter" helps, but not enough. Referring to an equalizer as "non-combining" is imprecise. All equalizers combine their filter outputs. The issue is how much ripple results.

For these reasons, Rane [18] suggested the term "interpolating" as an alternative. Interpolating means to insert between two points, which is what buffering adjacent bands accomplishes. By separating adjacent bands when summing, the midpoints fill in smoothly without ripple.

Fig. 8 plots the summed response of adjacent filters showing good combining or interpolation between bands for an interpolating constant-Q equalizer. Fig. 9 plots similar results for a proportional-Q equalizer. Fig. 10 plots the summed response of adjacent filters showing combined response with ripple for either constant-Q or proportional-Q designs not buffering adjacent filters. Demonstrated here is the lack of interpolation between centers.

Minimum-Phase Filters (or Minimum Phase Shift Filters). A much confused term, having little meaning for today's variable equalizers. There seem to be two issues intertwined here. The first concerns minimum-phase filters and the implication that some equalizers do not use mini-

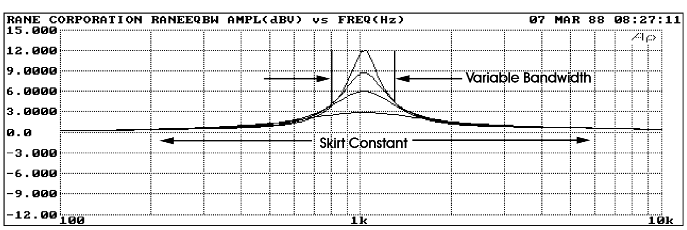

Figure 4. Proportional-Q (Variable-Q) equalizer performance.

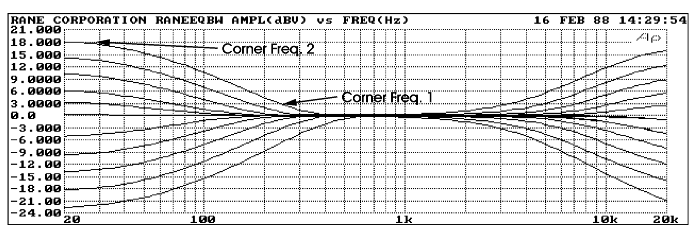

Figure 6. Equalization curves showing shelving response.

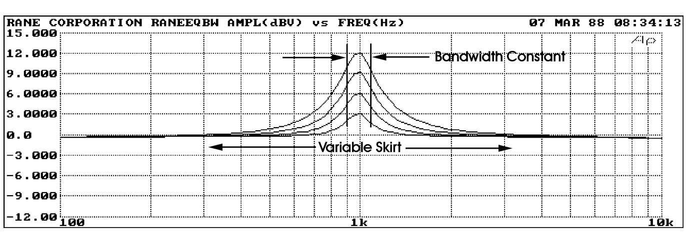

Figure 5. Constant-Q (bandwidth) equalizer performance.

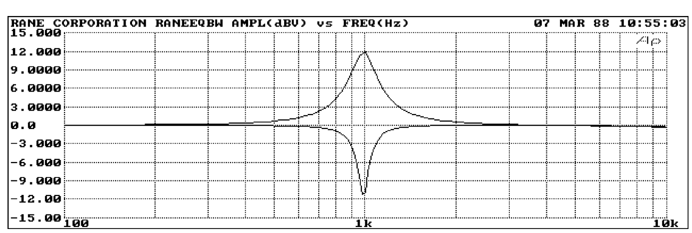

Figure 7. Asymmetrical (non-reciprocal) boost/cut curves.

mum-phase filters. From a strict electrical engineering viewpoint [19], [20], the precise definition of a minimum-phase function is a detailed mathematical concept involving positive real transfer functions, i.e., transfer functions with all zeros restricted to the left half s-plane. References [21] & [22] demonstrate that all equalizer designs based on 2nd-order bandpass or band-reject networks have minimum-phase characteristics. This says, in essence, all variable equalizers on the market today use minimum-phase filters.

The second issue involves minimum phase shift filters. There is an implication that some equalizers produce less phase shift than others. Again, this does not seem to be the case. All 2nd-order bandpass or band-reject filters (active or passive) shift phase the same amount. (The bandwidth of this phase shift differs for various 2nd-order responses, but the phase shift is the same.). And when used to create boost/cut responses, do so with the same phase shift. Different phase responses do exist, but they are a function of boost/cut levels and individual filter bandwidths. That is, there will be less phase shift for 3 dB of boost/cut than 12 dB; and a 1-octave filter set will have a wider phase response than a 1/3-octave unit (but the number of degrees of phase shift will be the same). Figs.11 and 12 demonstrate this. In Fig. 11, the phase responses for different levels of boost appear (cut responses are identical but mirror image). This verifies Pennington's [23] rule-of-thumb regarding 10 degrees of phase shift per 3 dB of amplitude change. Fig. 12 shows the bandwidth variation for this phase shift for wider and narrower bandpass responses.

This completes the most common variable equalizer terms. Other terms exist—lots—but this is the foundation for understanding the remaining variations and alternatives.

FILTER TYPES

Passive. Audio use of fixed passive equalizers dates back 50 years to Hollywood's early experiments with program sweetening. Harry Kimball published the definitive design book of the times [24].

Even before Rudmose and Boner, Frank Bies of Bell Labs described passive attenuation equalizer use for correcting overall gain-frequency characteristics [25]. These two papers represent early guidelines for fixed passive equalizer designs. The most successful topology was the bridged-T section. When applying variable techniques to bridged-T sections, however, the nuisance characteristic of changing loss appeared. That is, as you varied the amplitude you also varied the net loss through the filter section. Soloman and Broneer [26] did the pioneering work for designing constant-loss variable passive equalizers (constant-loss in the sense that varying the attenuation did not change the net loss).

They showed that redrawing a Wheatstone bridge creates a bridged-T equalizer (Fig. 13). In Fig. 13 the boxes labeled Z1 and Z2 consist of variously configured reactive (inductors & capacitors) elements. Named constant-S (S is the symbol for insertion loss) equalizers, Soloman and Broneers work paved the way for commercial passive variable equalizers employing constant-K (impedances independent of frequency) designs. Fig.14a shows a band-reject constant-S variable equalizer, while Fig. 14b shows the simpler commer-

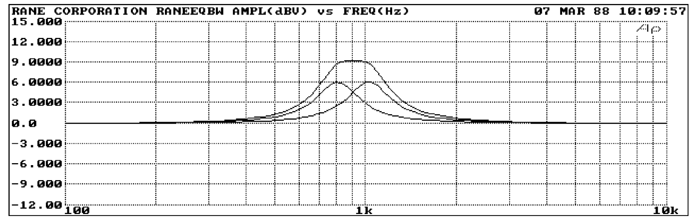

Figure 8. Summed response of adjacent filters showing good combining or interpolation between bands of interpolating constant-Q equalizer.

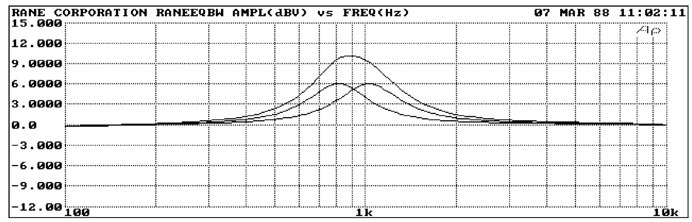

Figure 9. Summed response of adjacent filters showing combining or interpolation between bands for proportional-Q equalizer.

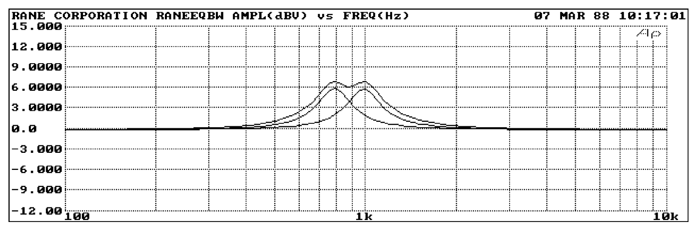

Figure 10. Summed response of adjacent filters showing combined response with ripple, for constant-Q or proportional-Q designs, not buffering adjacent filters.

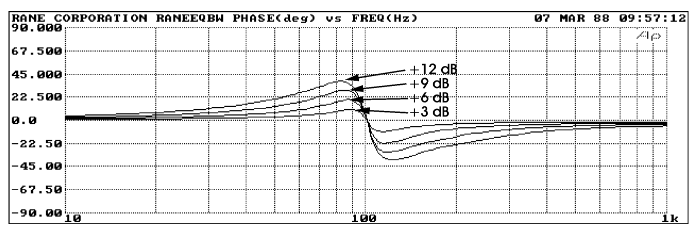

Figure 11. Phase response of 2nd-order bandpass filter used to produce four boost levels for 1/3 octave equalizer.

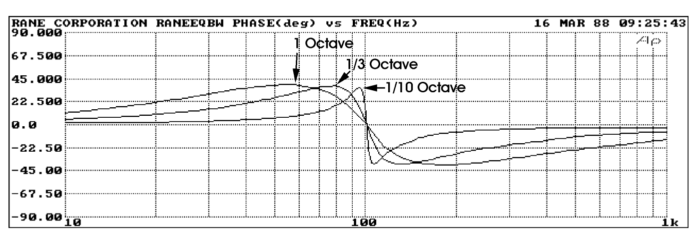

Figure 12. Phase responses for 2nd-order bandpass filter used to produce + 12dB boost levels for three bandwidths.

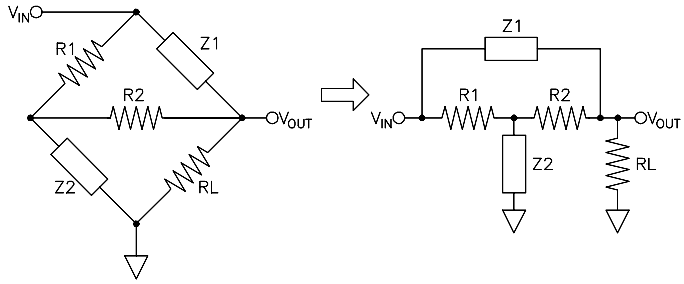

Figure 13. Wheatstone bridge to bridged-T equalizer re-drawing.

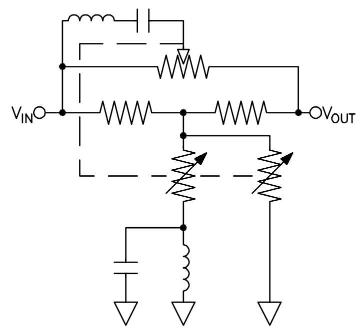

Figure 14a. Constant-S variable band-reject filter.

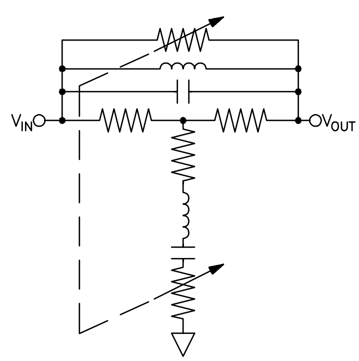

Figure 14b. Altec-Lansing Acousta-Voice band-reject filter section.

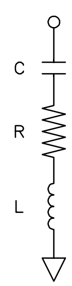

Figure 15. Series resonant network.

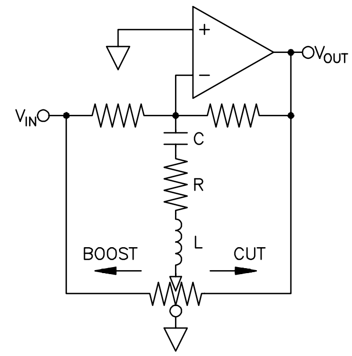

Figure 16. Active LC equalizer based on Baxandall negative feedback tone control circuit [27].

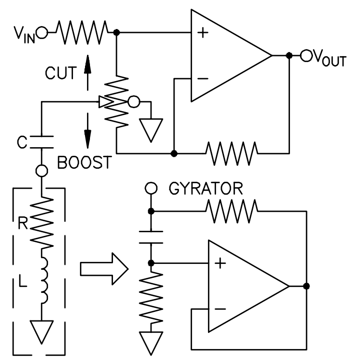

Figure 17. Active LC circuit showing gyrator substitution for inductor.

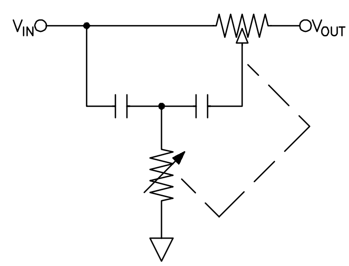

Figure 18. Bridged-T RC section used by API in active proportional-Q equalizer.

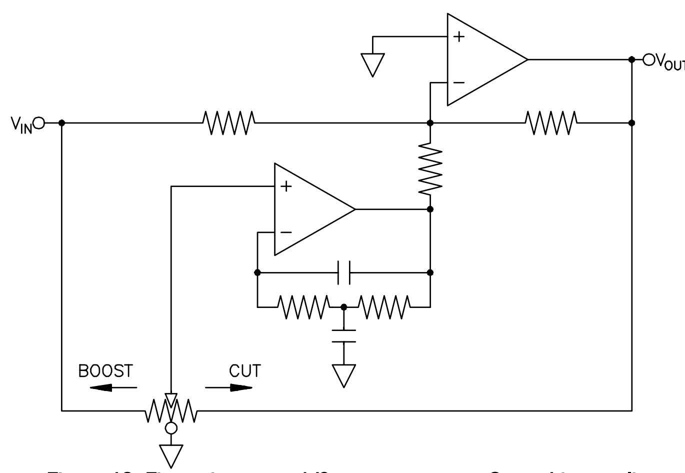

Figure 19. First private-use 1/3-octave constant-Q graphic equalizer circuit developed by Thurmond [30].

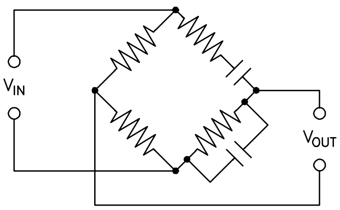

Figure 20a. Passive Wien-bridge.

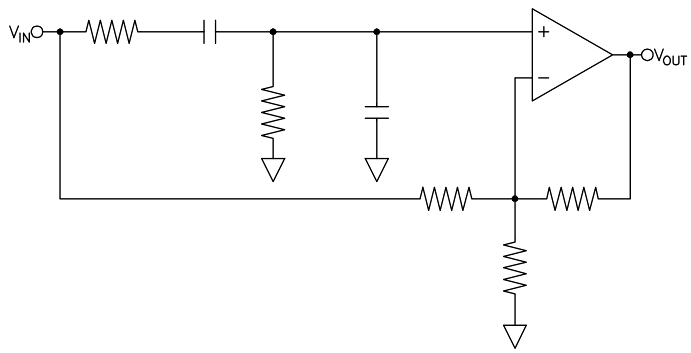

Figure 20b. Active Wien-bridge band-reject filter.

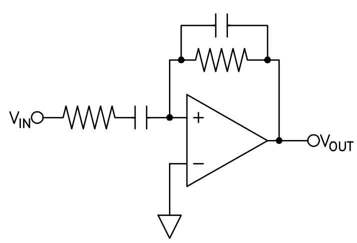

Figure 20c. Active Wien-bridge bandpass filter.

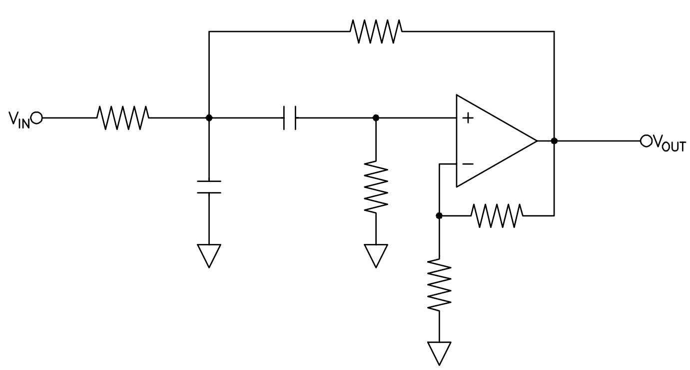

Figure 21. Voltage-controlled voltage source (VCVS) bandpass filter section.

cial network as first used by Altec-Lansing in their Acousta-Voice system.

Active LC. Active LC designs commonly use the simpler series resonant network (Fig. 15) over the more complex bridged-T configuration. A popular topology, based on Peter Baxandall's famous negative feedback tone control circuit [27] appears as Fig. 16. The LCR series resonant circuit creates a bandpass filter function. The slider routes the bandpass filter either to the input for boosting or to the output for cutting. This design is indicative of approaches used by White [21] and others.

Another often used design appears as Fig.17. Here the series resonant circuit is routed between the amplifier's inputs. When connected to the positive input, it acts as a frequency selective attenuator; and when connected to the negative input, it acts as a frequency selective gain booster. Altec [2], UREI and others favor this design.

Active RC Proportional-Q. Active RC filter techniques provide the means for creating very cost-effective designs. The most popular approach makes use of gyrators [28], [29]. This synthetic inductor replaces the series resonant circuit as shown in Fig.17. This is the most common proportional-Q design and perhaps a dozen different manufacturers use it. This is the simplest gyrator form; many others exist.

API, Audio Products, Inc. developed a unique proportional-Q approach that uses the bridged-T RC filter section shown in Fig. 18 as the variable building block. Many such buffered sections string together in series. Although drawn as single elements in Fig. 18, the capacitors are really a bank of capacitors selected by the frequency control.

Active RC Constant-Q. Credit goes to Bob Thurmond for development of the first private-use constant-Q, 1/3-octave graphic equalizer in 1973 [30]. (Commercially available constant-Q graphic equalizer designs did not become available until 1981 [31]). Thurmond used the Baxandall derived design shown in Fig. 16 and replaced the series resonant circuit with an active RC filter using a bridged-T feedback circuit. Fig. 19 shows a simplified diagram for this design. Today, Altec [2], Carvin, Dax and others use this basic topology, differing only in the type of bandpass filter used.

Active RC bandpass filters based on various non-gyrator topologies, appear in all constant-Q equalizer designs. Some use Wien-bridge based active filters as shown in Fig.20, but most use Huelsman's [32] designs derived from the monumental work of Sallen and Key in 1955 [33]. These appear as Fig.s 21 and 22.

Another commonly used technique relays on a circuit developed by many, but patented by Ken Gundry of Dolby Laboratories [34]. No mention appears in the patent regarding constant-Q performance advantages or parametric equalizer use, yet these are the most often seen variations. Fig. 23 shows this circuit. Comparing Fig.s 19 and 23 reveals their similarity. The main difference being Fig. 23 separates the boost/cut functions using two amplifiers. Rane, White and others use variations of Fig. 23 in their constant-Q graphic products.

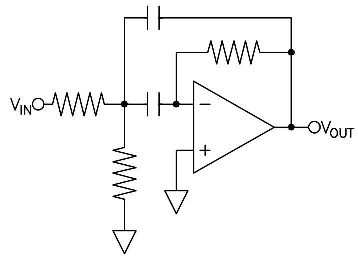

Figure 22. Multiple feedback (MFB) bandpass filter section.

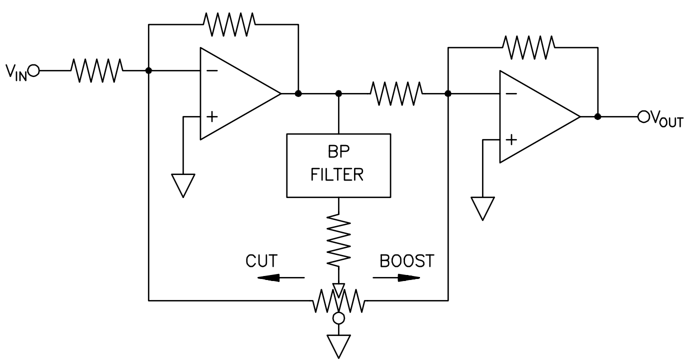

Figure 23. First commercially available 1 /3-octave constant-Q graphic equalizer circuit [31].

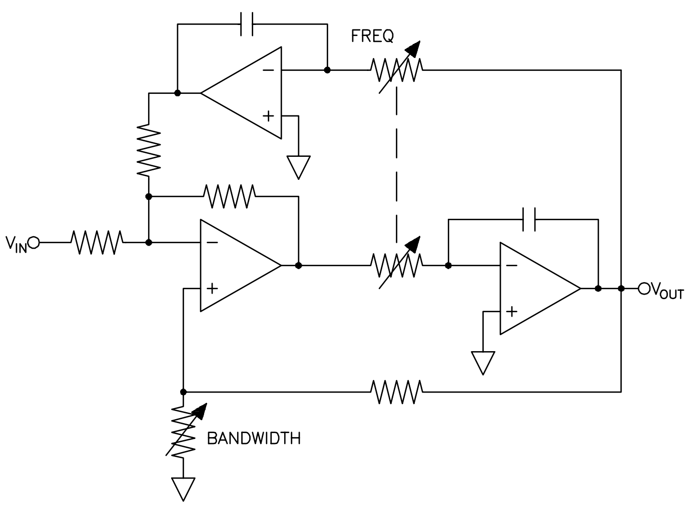

Figure 24. State-variable non-inverting bandpass filter section.

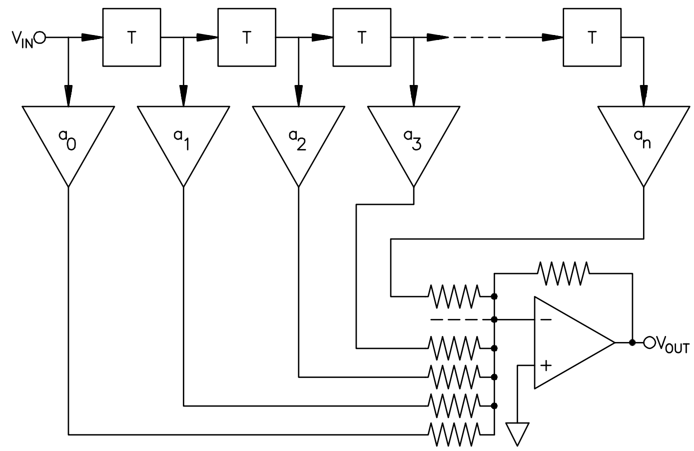

Figure 25. Transversal filter graphic equalizer.

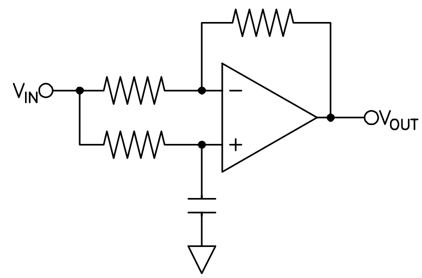

Figure 26. Simple all-pass filter delay block.

Parametric Equalizers. Parametric equalizer designs use many of the same circuits as constant-Q graphic equalizers (historically, the parametrics were first). By adding independently variable frequency and bandwidth controls, you create a parametric equalizer. A popular way to do this is to use a state-variable active filter as shown in Fig. 24. Carefully designed state-variable topology allows completely independent control over frequency and bandwidth without changing the amplitude. Relegating the amplitude control function outside of the state-variable filter then completes a true parametric equalizer. Any of Fig.s 17,19, or 23 work as parametrics with the bandpass function being replaced with the state-variable design of Fig. 24.

Transversal Equalizers. Transversal filter equalizers are constant-Q designs based on a tapped delay line as shown in Fig.25. Each tap roughly represents an area of the frequency response affected. Scaling each of these outputs by a "tap weight" (constants a1, a2, etc.) and summing the results, produces any desired frequency response. Active filters can be designed either in the frequency or time domain with the same results. Frequency and time are inexorably linked by physics. Transversal filters take advantage of this knowledge by modifying the frequency response using time delay (also the foundation for all digital filters).

Analog transversal filter designs require using either analog delay lines (bucket-brigade devices) or all-pass active filters. The simplest all-pass filter appears in Fig. 26. It produces a flat amplitude response with changing phase shift. (Interchanging the positions of the non-inverting input resistor/capacitor network produces either phase-lead or phase-lag characteristics). This circuit starts with zero degrees at DC, yields 90 degrees at the design frequency, and ends up with 180 degrees at high frequencies. Since time is nothing more than phase shift divided by frequency, you can use a string of phase shifters to create time delay (although it is frequency-dependent time delay; frequency independent time delay requires bucket-brigade devices or digital techniques). An all-pass filter approach produced the first transversal equalizer by IRP [13] in 1984.

CONCLUSION

So, there you have it—15 categories to choose from. To sum up, as the great London auctioneer Mr. Christie said, in 1770, "The whole of which is truly neat."

This many categories exist primarily due to simple historical evolution. As technology evolved, so did equalizer design. A natural course of events. Transistor and integrated circuit developments led to active designs. Invention of gyrators created a new category. Proliferation of modern active RC filter designs created new ways of doing old tricks, and old ways to do new tricks. And, today, digital technology propels us into a whole new generation of equalizers.

My personal favorite is the parametric. It allows you to go anywhere and do anything. Yet, there are those who claim the best parametric will not sound as good as old passive bridged-T designs. Perhaps, but that cannot be objectively proven. Tightly controlled A-B testing demonstrates that all equalizers designs, creating the same exact frequency curve (important—it must be identical) are indistinguishable. It does not matter whether they are passive or active, proportional-Q or constant-Q, LC or RC, fixed band or parametric, or operate in the frequency or time domain. With apologies to Gertrude Stein, a transfer function is a transfer function is a transfer function.

Differences do exist, but they are in areas other than those described above. Secondary considerations such as noise performance, dynamic range, and transient stability all enter into explaining perceived sonic attributes.

Many designs are decades old, while others are but a few years. The latest is not necessarily the best, although, we like to think so. Each new development is embraced as the ultimate—for a while. Then, we tend to migrate back to proven ways that are comfortable and known, if for no other reason. This, too, is not always best. Ours is a human industry, with human quirks.

The decision as to which is best is a personal one. Many subjective things enter into the selection process. There are those who swear by one design over another and will never be convinced otherwise. Nothing can be done about this, nor should we try. Objectively, much could be written regarding the performance virtues of each design. Nevertheless, suffice it to say, applications exists for all these designs. Eventually, the market determines lasting favorites. For now, *vive la difference*.

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