

# Toroidal O.T's in Musical Instrument Amps

By: Kevin O'Connor

## Perspective

Historically, musical instrument amplifiers followed typical hifi construction and design patterns until it was realized that certain economies could be made. Many early amps had inputs for microphones, accordions, guitars, tape decks and even phonographs. This meant that the amplifier should ideally reproduce any of these sources with reasonable accuracy, which in turn meant that the power bandwidth should be wide. While the demand for more power tended to drive costs up, specialization of musical instrument amps for specific instruments reduced the power bandwidth required, keeping costs low.

The guitar has a fundamental frequency range starting around 80Hz and going up to nearly 1,500Hz. Each note has harmonics that are multiples of these frequencies, which allow you to recognize the instrument as a guitar in the first place. The spectral balance of fundamental to harmonic energy gives the guitar its 'timbre', or 'voice'. So, no two acoustic guitars will sound exactly the same – and surprisingly, neither will two electric guitars.

A bass guitar has a similar frequency range but starting an octave lower. The lowest note on a standard four-string instrument is around 40Hz, with its highest note around 750Hz, and harmonics going higher.

For either instrument, the frequency range is narrower and lower in pitch than most of us would expect. This is because the fundamentals and most of the harmonics lie in the critical 'mid-range' where human speech occurs. Our hearing is most sensitive in this range, and there are many peaks and dips in our individual and group hearing sensitivities that allow us not only to hear noises from our own kind, but also noises from ancestral predators and prey, which is why we are still here today.

There is actually quite a lot of clutter in the midrange from many instruments with overlapping frequency ranges. This is one reason

why manufacturers tailored instrument amps for only one type. Musicians often plugged two or more instruments into one amp in the early days. This worked well as long as the amp was operated in its linear range – that is, if the sound was 'clean'.

As stage volume rose, it became more difficult to keep the sound clean enough to distinguish the instruments. Those early amps had inefficient speakers with little power to drive them. More power was easy to get, so ratings were increased and speaker sizes increased to match.

Ironically, the speakers used for guitar are what most people would consider to be 'woofers'. These are large diameter cone speakers with very little high frequency response. In the typical open-back cabinets, which were economical to build but could support the amp chassis and speaker as a complete unit called a 'combo', the bass response was also poor. With many guitars, and always with bass – unless played very quietly – the speakers would 'flop out' on the very lowest note. This meant that the cone would hit the basket or speaker frame at one extreme – called 'bottoming out', or be over-excursed at the other. Sounded terrible!

The combo format was very inexpensive to make, so manufacturers were not about to change it. It did provide some ventilation to the tubes and electronics, since there was literally no back on the cabinet. Most chassis were placed at the top with the tubes hanging upside down, which is still done today. Another variation was used in the fifties and is sometimes called the "tweed" format. Here, the chassis is bolted vertically to a short back panel, and the tubes either hang upside down or point inward horizontally. Any of these constructions represent a severe environment for the tubes themselves.

Tubes are a mechanical assembly that relies on the geometric alignment of various structures to yield intended performance.

If the alignment of these structures is compromised, performance can suffer and the tube can experience catastrophic failure. Most tubes die because of mechanical upset long before they are worn out electrically, so it seems counter-intuitive to intentionally place glass envelope tubes in a strong vibration field. But that is exactly what is done in a combo amp.

Fortunately, the change that saves our speaker also extends tube life. The only 'fix' that will keep our speaker from bottoming-out on low notes is to reduce the energy of those notes. We can filter them out electronically in the preamp, or, save some money and weight by reducing the bandwidth of the output transformer. As it happens, this is what every manufacturer did starting in the fifties, and the elements for the "classis" tone were established: functional electronics, narrow-bandwidth output transformers, saggy power supplies and stiff-suspension woofers in undersized cabinets.

## Evolution

We are trying to get treble out of a mid-range instrument played through a woofer.

Strange but true.

Traditional players who still use a relatively clean sound, use the frequency shaping of the speaker, the warmth of free-running tube gain stages and a limited bandwidth power amp to achieve their desired tone. That tone is completely subjective in nature, and each player seeks his own personal tone. Nuances become important – more so than gross differences.

Modern players dabble with distortion textures. These may result from over-loading the power stage just a bit, or quite dramatically into continuous clipping. This type of distortion becomes difficult to equalize to taste using the tone controls on the amp, since these are before the 'distortion generator' in the signal chain. In this case, gross equalisation is provided by the speaker itself.

As distortion became a more desirable feature, its character became more critically debated and many manufacturers produced 'small-signal' devices to achieve these tones. This led to the rivalry between advocates of 'output tube distortion' versus those for 'preamp distortion'. Proponents of the former tended also to have the agenda of tube sales. Certainly, preamp distortion is easier to control and does not require that the player use his amp at maximum volume all the time. This means the speaker is also less likely to be damaged, since the clipped output of an amp is a squarewave, which quickly overheats the voice coil. If the preamp is distorting and the power amp is running clean, then the speaker is not likely to be pushed as hard to begin with and will survive longer even though the waveshape here might ultimately be the same as in a clipped amp.

Along with electronic developments and changes in musical tastes, speaker cabinet formats became more varied. The separate amp 'head' and cabinet is popular, as are rack-mounted electronics packages. So, these days, there is a market for every kind of musical instrument product and every design philosophy.

## Toroidal Attributes

The need for extreme bandwidth limiting in guitar amp output transformers has diminished dramatically in the past decade or so. Some manufacturers historically used 'over-sized' transformers and achieved a certain signature tone for their products. Over-sized in this sense really means that a full-bandwidth device is used. Such upgrades can be difficult on some older chassis where space is at a premium. This is one place where a toroidal output transformer has an advantage. For a given power bandwidth, the toroid will be half the volume and weight of a traditional EI, or square transformer.

Most players today are trying to get the same tone at low volumes that they used to get only at high volumes. This means that generally distortion and bulk tone is created in the small

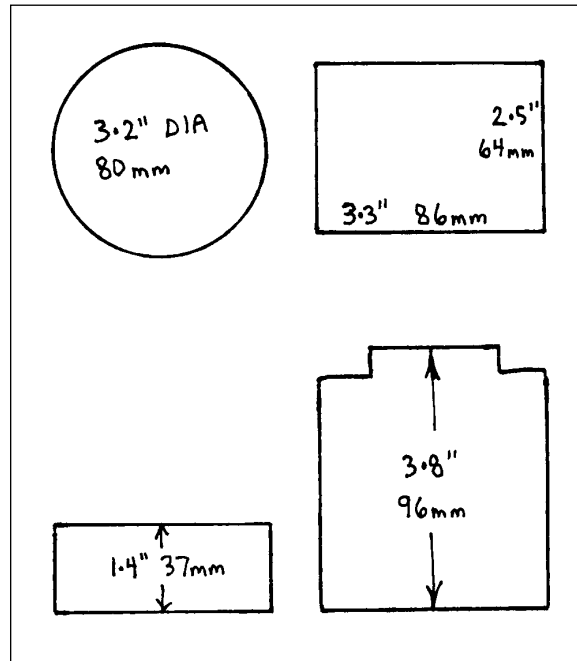


Fig. 6-1: 20W toroid OT compared to 20W EI

signal domain. The power amp and speaker will contribute to overall tone, but now, not to distortion. So, the power amp and speaker should almost be hifi in nature. How far one takes this depends on individual tastes. Dynamic distortion in the 'power end' is no longer an attribute. Here, toroids have another advantage, as their magnetizing currents are lower and their inherent linearity is greater.

There are many icons of tone in the market. Some are brand-specific and some are not. One that is not is the sound of a 100W amp compared to the sound of a 50W amp. Most players who have the opportunity to try a manufacturer's 50W and 100W models side by side find the larger amp to be more "open", more "solid" and "unrestrained". This is at any volume that both amps can achieve.

'Big amp' sound is generated by known factors. The most obvious of these is the presence of a larger output transformer, usually with lower

impedance windings. There is usually a doubled-up output stage with four output tubes instead of two, since most 50W and 100W amps in the same model line operate with the same tubes, circuits and voltages. In this case, the impedance presented by the active devices is lower, too. The big amp usually has a bit more filter capacitance in its supply to support the B+ rail under peak output conditions with minimum ripple. And, of course, the power transformer will have a higher current and, again, lower impedance plate winding. Since the big amp has increased capacity in many domains, the resulting sound is actually cleaner.

Another form of distortion is reduced in the big amp with its larger capacitance. Nearly all production and custom built amps use electrolytic capacitors to filter the various supply rails. The high dielectric absorption, dissipation factor and poor frequency response of most electrolytics – especially the cheaper types used in dollar-driven guitar amp designs – contribute a veil of distortion that is worse with lower capacitance values and with aging of the capacitor. The doubled-up values often found in larger amps reduce the level of this distortion for the "unrestrained" sound. This is why hifi designs specify much greater capacitance values and better grades of capacitor, and often by-pass them with film caps. Intuitively, the power supply is just some support circuitry and should not affect tone, but its dynamic impedance is in series with the signal path. Any distortion mechanism in the supply is therefore relevant as it might as well be a fault with the audio circuitry proper.

Toroidal output transformers tend to have low impedance windings, to take advantage of their other magnetic properties and yield maximum performance. The Standard Line of output transformers produced by Plitron demonstrate what can result when insightful design is combined with careful production. These designs were developed by Menno Vanderveen and the team at Plitron, who together devised proprietary winding methods and pushed the envelope of the prevailing technology even for toroids. The later Specialist series pushed these limits even further.

There is yet another advantage to toroids that makes them particularly well suited to instrument amps: they have little or no magnetic radiation. Most musical instruments have electromagnet transducers to convert the vibration of metal strings into an electrical signal. These pick-ups are also prone to electromagnetic interference usually caused by power lines, lighting control dimmers, and the transformers in the amp itself. There is a proximity effect players experience when they walk up to their amps, where the buzz from the amp increases as they approach. Holding the guitar at various angles will change the nature and loudness of the buzz, which can be quite problematic on smaller stages where no “sweet spot” can be found for minimum noise.

## The Circle of Life

So, what good is a “super transformer” in a guitar amp? For one thing, these transformers have incredibly wide bandwidth and are extremely linear. This reduces the distortion contributed by the transformer itself and makes applying feedback around the device easier.

In a traditional guitar amp, there are only two gain stages within the feedback loop: the splitter and the output stage. Almost every guitar amp built since the early sixties uses a Schmitt splitter with feedback applied to one side and the input signal from the preamp applied to the other. The outputs of the splitter have similar enough impedances and frequency response to be stable without any compensation internally or externally. Any peaks or dips in the response of the average EI transformer do not cause any worry.

In the nineties, many designers and tinkerers have been playing with “hifi” front-ends for their instrument power amps. These often use three and four stages of gain within the feedback loop. The peaks and dips of that EI device suddenly become problematic. So, internal compensation, over-all group delay compensation, some positive feedback, and nested loops become necessary for stability into a load, and particularly at clipping.

Plitron’s output toroids behave like second-order low-pass filters but with wider response than most amp circuits. So, their inclusion in the feedback loop of these more complex circuits makes life a lot easier. They have impeccably flat response, and thus do not upset the loop or introduce phase shifts within the audio band. Menno has done a fantastic job here!

What started as a general purpose amplifier for musical instruments – really, a portable hifi amp with built in speaker – evolved into a specialised single instrument amp, and has again become nearly a hifi amp. You might want to blame ‘boutique amp’ builders for this, but it is also a market trend.

‘Hifi’ is still a dirty word in some musical circles. There is the implied cleanliness – even sterility – of tone. It *can’t* be good for warm guitar tone? Can it?

Well, wouldn’t you know, Menno and nearly everyone at Plitron play guitar or some other instrument! They came up with a line of toroidal output transformers specially designed for musical instrument amp use. This is not entirely surprising, though, as Plitron has been custom building toroidal output transformers for instrument amp manufacturers since at least 1995. They produce some now-standard bass amp OTs rated at 300W and 400W, that OEMs have been using successfully, and some complementary power transformers are in the works. We’ll talk about these later on.

## The 4157

The first dedicated standard ‘guitar’ toroid that Plitron developed was the 4157. This is rated at 20W with a plate-to-plate impedance of 8k $\Omega$  when driving an 8 $\Omega$  load. There are no UL taps or other impedance taps. This was designed primarily to match a pair of small tubes like EL-84s, 6V6s or 6V6s into a single speaker. Of course, if you have a pair of 16 $\Omega$  Bulldogs you would be close to Vox-heaven.

My first test with the 4157 was fairly informal. I tied it into my own 20W amp that I use for guitar and bass. The 4157

sounded ‘bigger’ than the custom EI transformer that the amp was designed around. There was a bit more of that ‘unrestrained’ tone that you would have with a 40W or 50W amp. In fact, this sounded almost as good as my 120W bass reference amp! This is definitely a “plus” for the 4157. I was lucky enough to talk to Menno, and he told me that the wire gauges were deliberately over-spec-ed, and that this would contribute to this sonic effect. Lower impedances, again.

I have an old Fender Twin chassis here, that I actually used as my own amp for quite a few years. It never had a case – I would just bring it to jams ‘exposed’ and sit it on two heatsinks. It had been completely rewired and there was nothing left that was ‘Fender’ except the power supply. For this test, though, and because I do not use the amp anymore, I rewired the stock Fender Twin circuit. I hooked up the 4157, which at first glance looks like a major mistake. The amp has a B+ of 470V but the 6V6s that had been in there for more than a decade did not seem to mind. Menno warned me that the prototype 4157 was not insulated for such high voltages, especially considering that the end-to-end voltage across the primary could approach 800V or so. My intention here was just to hear how the 4157 would sound compared to the Fender OT and a larger Hammond unit that normally lived in this amp. I was not going to run the unit to the maximum output of the amp, just check the tone.

The 4157 is surprisingly – or not so – about the same weight as the stock Fender OT, which is a channel-mount. This tells you right away that the original device is very limited in its power output at low frequencies. The 4157 has a corner frequency of 57Hz, which is more than adequate for guitar, so the Fender must roll off much higher than this – at least 100Hz. To make comparisons a little easier, I put a switch in to do quicker A-B comparisons.

The Twin is known for its clean, warm, loud tone. The stock pair of 12" speakers push a lot of air, but the bass is not



muddy since the OT rolls it off. Some players describe a 'spanky' tone, which means it has good transient attack without too much 'clicking' from the sound of the guitar pick hitting the strings. This attribute is actually related to the preamp design, so changing the output transformer does not affect it at all. The 4157 sounded every bit as good, and maybe slightly more open. It was very close. The 1600-series Hammond unit that I normally used sounded a bit bigger, but then it is twice as large as the Fender transformer.

I had some local musician friends help with this audition, so it was a group consensus and not just one person's opinion.

For a final comparison, I tacked the 4157 into my 120W bass amp. It sounded good here, too. Not quite as huge as the stock OT, but quite good. At a 1W level, my reference speakers produce about 100dB of sound at one meter, so this test was at less than a 1W level. You may doubt the validity of such a test, but this is the power level where most musicians practice - particularly at home.

An EI transformer, or any type for that matter, will exhibit a wider response at these levels than at full power. So, a listening test at typical levels means there is less than 1W of electrical power required.

## A Round Peg in a Square Hole

The only problem with toroids is that most chassis are square and space is limited. In some cases, the foot-print of the toroid lying flat requires more space than the stock EI transformer. The solution is to mount the toroid on a vertical bracket. The prototype 4157 has a neoprene pad on its underside, with an epoxy potted centre with a hole drilled through it. The leads come off the top outer "edge" of the toroid.

The L-shaped bracket should be about 76mm (3") wide and about 90-100mm (3.5"-4") tall with a mounting hole for the toroid. The foot of the bracket should be about 12-25mm (0.5"-1") wide with at least two screw holes. These can be lined up with the original holes

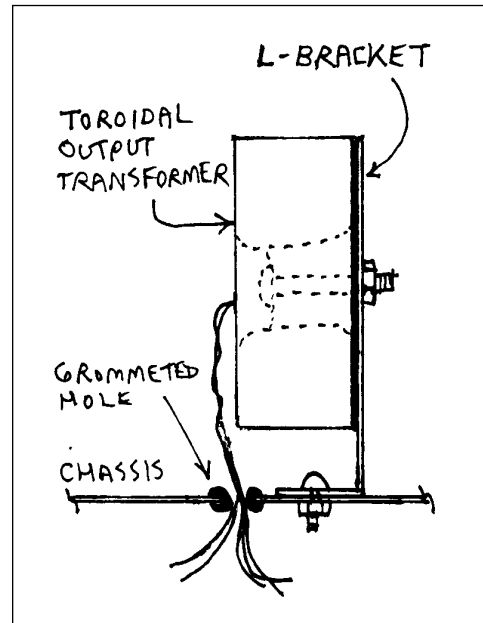


Fig. 6-2: Vertical bracket for retro-fitting

or spaced for best stability. The leads from the transformer come off at two points - three primary wires and two secondary leads. Each group should be twisted together and fed through the grommeted chassis holes where the original transformer leads passed through.

On the Twin chassis, I could use the original transformer mounting holes to secure the 4157 for extended tests. Unfortunately, the Fender chassis is only 8" wide from front to back, and the front inch and a half must be kept clear to pass through the cabinet opening, for a stock combo set up. There is not enough space to lie down a toroidal power transformer, but...

If one were to make an extended L-bracket, wide enough to accommodate the larger diameter Standard Range power transformers - say the Plitron 754709 or 854710, which are both about 6" in diameter - then the power transformer could be toroidal, too. The electromagnetic radiation from this transformer set would be next to nothing - certainly 30-

40dB lower than the stock transformer set. This "Toroidal Twin" would sound bigger than a stock 100W Twin, but in fact be no heavier. You could retain the power rating by using a Standard range output transformer like the PAT-4004 (70W) or PAT-4006 (100W), or the instrument output PAT-4151 (90W).

Note that if you were rebuilding the amp as a head, or if you had started out with a Dual Showman, the vertical bracket for the power transformer could be a simple L-shape and fairly short. For a combo amp, you need to clear the speaker and the close-spaced power tubes. A longer bracket is needed, and it must have a bend in it as shown in Fig. 6-3.

You could further reduce radiation and hum inside and outside the amp by replacing the single-ended reverb transformer and driver with a push-pull circuit, such as the London Power push-pull circuit shown in "The Ultimate Tone vol.2". The Toroidal Twin reduces proximity-buzz to nearly nothing, provided the top of the chassis is covered with metal.

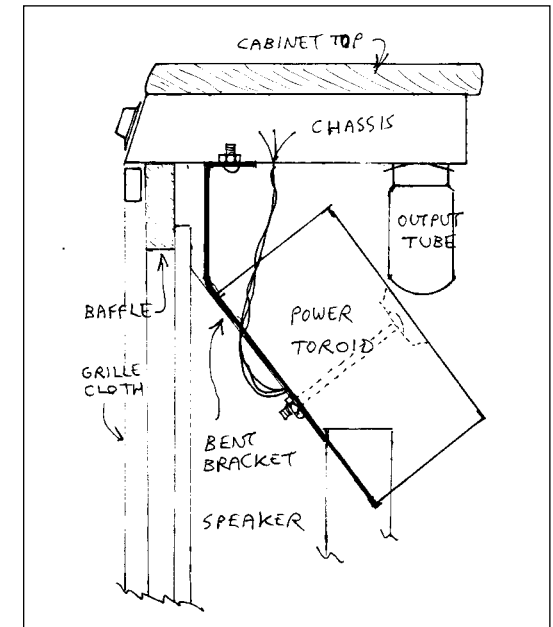


Fig. 6-3: 'Bent' bracket for power transformer

## Further Tests

To put the 4157 through its paces, I built a test fixture that used a 754709 as the power transformer. This allowed a maximum B+ of 470V. I built a Power Scaling supply so that I could vary the voltage fed to the output transformer and its driving circuitry. For versatility, four octal output sockets and four 9-pin miniature sockets were wired up for various output tube configurations. Bias was switchable from fixed to cathode bias, and two front-end circuits were set up, selected by a multi-pole switch. A typical two-stage preamp with EQ between the stages was also included to make the unit useful with guitar. Feedback was switchable.

These features allow a typical Fender or Vox circuit to be simulated quickly. The variable supply allows some measure of safety for the 4157, as well as allowing one to see how low or high the B+ should be for each configuration.

Set up as a "Fender" amp, with fixed bias, the 20W rated output is achieved with as little as 324V with four output tubes, or just 335V with a single pair. Cathode biasing requires a B+ that is about 25V higher. This simulates a Vox-style output stage, which is cathode biased. Opening the feedback loop yields a more Vox-like tone, especially with EL-84s selected.

One option you have with lower powered amps is the use of practically any type of output tube. These can be chosen wholly for tone.

Since the 4157 is in fact an impedance ratio device, you could place a 4 load on the output, reflecting a 4k $\Omega$  plate-to-plate load to the output tubes. The extra heavy wire used to wind the 4157 really becomes beneficial here. A scant 200V-peak signal into the transformer produces full output! In fixed bias, this requires a supply of 240V and less than 270V for cathode bias.

You can take the power level up a notch, which is particularly useful in the 4 $\Omega$  mode.

To produce 30W into 4 $\Omega$ , just as in a Vox AC-30, requires a 245V-peak signal into the primary, at just less than 300V B+ for fixed bias. You can go to 40W in cathode bias quite easily, with only a 330V rail. In the 8 $\Omega$  mode, 40W requires a rail of 440V at load, with fixed bias. This is a bit beyond the prototype's insulation for more than a quick verification, but production units will handle this easily.

Some people still worry about "mismatched" impedances – that is, not having the nominal load impedance be the same as the nominal secondary impedance on the output transformer. Transformers are designed with a "nominal" match that assures the rated power at the rated bandwidth. Usually, a load other than nominal value will reduce bandwidth, power output, or both. With an EI transformer, this is audible but tolerated over about a 2:1 ratio in most cases – at least with properly designed units. The wider initial bandwidth of the toroid means that a reduction of bandwidth due to mismatch is hardly noticed. In most cases, the narrowing is still outside of the pass band.

In our tests, the mismatching of the load made little difference to the tone. It would be more noticeable in the "over-powered" conditions where bandwidth is already compromised slightly. Still, because the toroid has an inherently 'big' sound, the most extreme combination of over-powering and load mismatch would result in a sound comparable to an EI device designed for that same condition.

## Toroids in Real Amps

So, the toroid has many advantages, some of particular interest to musical instrument amplifiers. Why, then, aren't more guitar amps built using toroidal outputs and power transformers?

To date, the only reason has been cost. Toroids are more expensive to wind than EI devices, and because of that, they were initially targeted at peak performance

applications. Instrument amps are generally designed for pure functionality, at least with regard to the transformer sets. Until recently, there has not been enough market interest in toroids to make them viable, "but the times they are a changin'." Many consumers are fed up with manufacturers telling them what they should want, and lots of smaller companies have found that a commitment to quality is appreciated, and well paid for.

One of the first areas where toroidal output devices were used successfully is in the bass amp market. The industry standard for bass was the venerable Ampeg SVT, which used six 6550s to produce 300W. The low end roll off provided by the output transformer saved a lot of weight, but still, these are very heavy amps. Note that the recent re-released SVTs use even smaller transformers. This weight is cut in half when toroids are used, and with a slightly less extreme weight reduction, bass response can be extended (Plitron device PAT-4164).

In a new design, and even in the SVT, the 4164 offers a linearity improvement with its separate screen winding. You could opt for a bit more power – 400W from eight 6550s through the PAT-4141. This will fit into 3 or 4 rack-spaces and is therefore quite compact as high powered tube bass amps go. In my own company's SPECTRUM amp, 700W is produced with a single pair of output tubes, in 4U. All of these new toroidal amps have the extended low-end that 5- and 6-string bass players need, or those bassists into more aggressive styles. Yet, there is still the ability to create traditional, round tones.

The future looks even brighter for the use of toroidal power and output devices in musical instrument amps. Transformer winding techniques are constantly being refined and production processes made more efficient, and thus less expensive. As more people use toroids production quantities rise, further reducing the costs to



everyone. Companies devoted to quality will be the first to utilise these devices, and educated consumers who are not frightened off by "new" technology who will appreciate them – but if market trends continue, toroids may eventually reach the mid-price consumer as well.

## Plitron's Current Line of Toroids for Instruments Amps

PAT-4143	40W Guitar	4xEL-84 / 6V6
PAT-4141	400W Bass	8x6550 / KT-88
PAT-4151	90W Guitar	2xEL-34 / 6L6
PAT-4157	20W Guitar	2xEL-84 / 6V6
PAT-4164	300W Bass	6x6550 / KT-88

**Note 1:** The 4143 is designed for the unique over-load characteristics of the EL-84 in pentode mode.

**Note 2:** The 4146 has a separate screen winding for operation of the screens at a lower voltage.

**Note 3:** The 4151 is very low profile and will fit into a 1U rack case, with the tubes horizontal, or external.

Kevin O'Connor is a Canadian designer and author whose company London Power sells his Power Scaling amps around the world. Power Press Publishing produces his books, which help techs and hobbyists understand tube equipment and find their own tone.

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## Books by Kevin O'Connor

"The Ultimate Tone: Modifying and Custom Building Tube Guitar Amps" 1995 Now an industry standard.

"Principles of Power: A Practical Guide to Tube Power Amplifier design" 1996 Features circuits for the Plitron Standard Range of toroidal output transformers and matching power toroids.

"Tonnes of Tone: Electronic Projects for Guitar and Bass" 1996

"The Ultimate Tone vol.2: Systems Approach to Stage Sound Nirvana" 1997

"Ready Set Go!: An Electronics Reference for the Everyman" 1999

"Designer Notes: Constructing Tube Audio Gear" 1999 Features construction and design projects using Plitron toroidal transformers for guitar and hifi, including the preceding article

## The PAT-4157 Musical Instrument Output Transformers:

### Designers Note

The PAT-4157 is a very special design. When looking at the frequency range, one easily will recognize the limited bandwidth, only meant for guitar amplification. The lowest guitar string (the E) vibrates at 80 Hz, so a wider bandwidth below 80 Hz is not needed for. The same situation is encountered at the high side of the bandwidth where a 2-nd order roll-off at 25 kHz -3dB is seen. This is so totally different from our standard wide bandwidth designs. Here something special is going on. What is not visible in the specs, nor in the various graphs, is that a very special core material is selected for this output transformer. The magnetic behavior of this special core is used as a tone shaping device, strongly attributing to the tonal character of the electric guitar amplifier. Here the OPT is used to shape the finest tonal character and the softest overload behavior when overdriving the amplifier to pure saturation, giving the amp a tremendous sustain. This is other stuff, this is using the OPT as a musical instrument itself. Read Kevin O'Connor's (London Power Amps) article about his adventures with this new OPT, and the higher power applications he has designed for it. This transformer is one of the examples of our new range of Musical Instrument OPT's.

Menno Vanderveen

