The Tube Sound and Tube Emulators

Eric K. Pritchard

Are tubes magic? is there really a difference between tubes and transistors? Some hear the warmth and appreciate the full body of the tube sound, and others deride the thought. Is the magic of the tube sound more than mere nostalgia? A recording engineer, Russell O. Hamm, could hear the difference. Determined to find and explain the difference, he began testing microphone preamplifiers of various technologies. His famous paper, "Tubes Versus Transistors; Is There an Audible Difference?" [1], shows that the harmonic structures in overdrive conditions for different technologies are quite different, almost like fingerprints.

More recently, an electronics engineer, the author, started down the circuitous path to bring the two worlds together and to give solid state the character of tubes. The elusive tube sound has finally succumbed to an intensive research and development program that has produced solid-state tube emulators and tube emulator circuits [2]. The effort began nearly seven years ago with the search for a solid state guitar amplifier that sounded like tubes. After snaking through myths and theories, the research turned to emulating the tubes, both triodes and pentodes.

Eric K. Pritchard is president of Deja Vu Audio, Berkeley Springs, WV 25411

Russell Hamm's work provided a test and an independent source of data to correlate the operation of the triode tube emulator.

TUBES AND THE TUBE SOUND

In retrospect, the tube has many technically superior aspects, it is fairly linear, its operational parameters do not vary badly, at least for tubes of yesteryear.

It operates reasonably without feedback. Its gain-bandwidth product is not low, about 8 MHz for a 12AX7 in a generic audio stage, compared with 3 MHz for typical audio operational amplifiers. Tube parameters do not vary as badly as semiconductor parameters.

They do not have the widely varying input voltage threshold of FETs. Tubes, in fact, may be the most natural amplifier. Unfortunately, they are large, they are fragile, they are microphonic, they drift, they burn out, they are nearly obsolete, and they are rapidly becoming unavailable.

The tube sound has been so elusive that many consider it to be mysterious and beyond the capability of modern instrumentation. This is partly true. The tube sound is often more subtle than the oscilloscope display. Low level harmonics are not visible, but are audible. Distortion meters do not consider individual harmonics, but our ears do. Standard audio tests do not tell the whole story.

Russell Hamm moved beyond the Total Harmonic Distortion measurement and developed a test that separated different types of microphone preamplifiers: triode, pentode, transistor, and operational amplifier. This test measured and plotted the percentage of each harmonic as a function of overdrive.

The harmonic character of these preamplifiers, *Figures 1* through 5

[1], are quite different, virtual fingerprints of the various technologies and their respective circuits. The triode curves, *Figure 1*, show significant second harmonic generated by the bias shifting in the coupling capacitor created by grid conduction. The pentode curves, *Figure 2*, show the grid conduction delayed by the plate load curve going through the saturation region well below the knee into the high plate resistance region. The semiconductor preamp curves, *Figures 3* through 5, show no equivalence to grid conduction. The operational amplifier, *Figure 5*, shows the rapid rise in distortion created by high gains and substantial feedback.

The second harmonic provides punch in contrast to the blanket of the third harmonic [1]. Consequently, these figures show that the triode, *Figure 1* initially provides a blanketed punch that fades into a lot of punch. The pentode is primarily blanketed with a little punch. Semiconductors vary from quite blanketed to completely blanketed.

The next remarkable feature is the generation or rather the lack of high order harmonics. The high order harmonics, especially odd ones, put a discordant edge on the signal. A prime source of high order harmonics is feedback. Although feedback corrects for amplifier errors, it also attempts to correct for power supply limits. The feedback slams the output against the power supply rails and creates sharp corners that translate into high harmonics. This is quite evident in an operational-amplifier-based preamplifier, *Figure 5*. A transistor amplifier patent, in

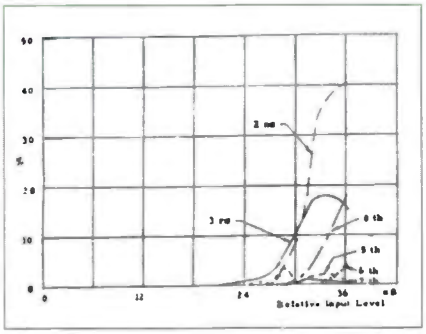

Figure 1. Distortion components for two-stage triode amplifier.

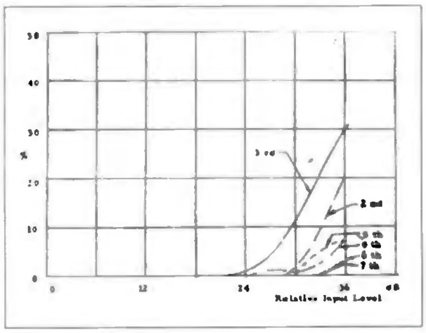

Figure 2. Distortion components for two-stage pentode amplifier.

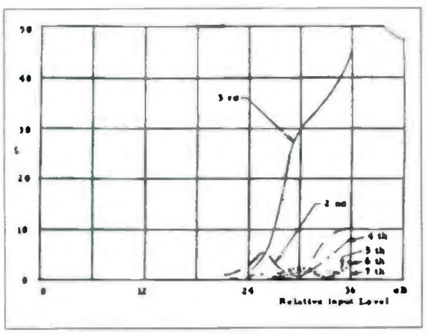

Figure 3. Distortion components for multistage capacitor-coupled transister amplifier.

an attempt to sound like tubes, has reduced the extent of feedback to avoid these problems [6]. Tubes, being more natural amplifiers, need less feedback and consequently do not generate as much of these high, harsh, discordant harmonics.

Tubes, particularly triodes pro-

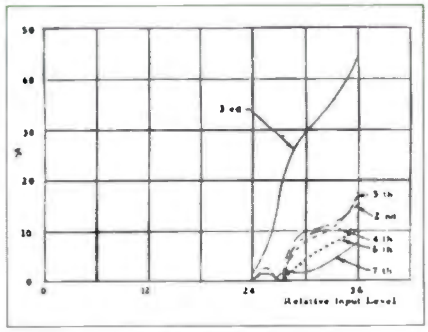

Figure 4. Distortion components for multistage transformer-coupled transistor amplifier

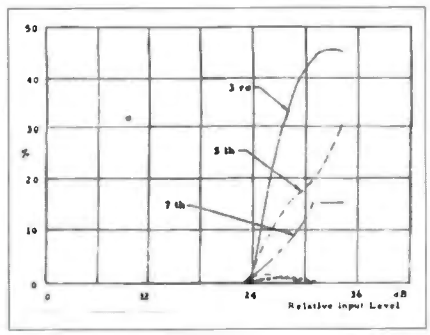

Figure 5. Distortion components for monolithic operational amplifier with hybrid output stage.

duce significant second harmonics, *Figure 1*. The second harmonic has two sources: the non-linearity of tube characteristics and the interaction of the coupling capacitor and the grid-to-cathode diode [7]. The non-linear characteristics are the plate resistance and the gain. The plate resistance and the gain produce harmonics at all signal levels. These harmonics are superseded by those created by the interaction of the coupling capacitor, grid-to-cathode diode, and clipping. The grid-to-cathode diode charges the coupling capacitor when the grid conducts. The resulting change in charge creates an offset that shifts

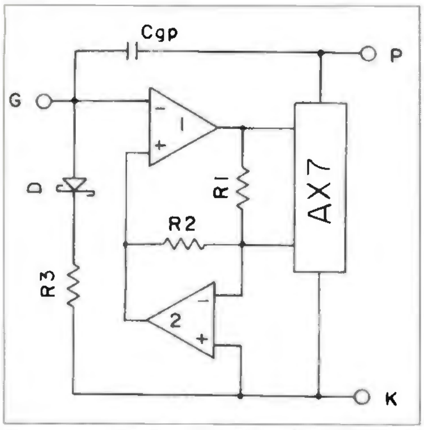

Figure 6. Complete Tube Emulator for a 12AX7

the bias from quiescent conditions. This bias shift alters the duty cycle of the resulting waveform. A duty cycle which is not 50-50 produces even harmonics. The two harmonic sources plus the low feedback combine to produce harmonics that occur over a wide range of input. This range is far wider than found in typical transistor or semiconductor designs. By comparison then, they distort too fast.

The grid conduction plus the unique plate characteristics give triodes the soft clip characteristic. Triode plate resistance is unique because the plate current sweeps upward with increasing plate voltage. Other devices, pentodes and all semiconductors, have a sharply rising current in the saturation region that then bends over into a constant current region. The triode plate characteristic ensures that for moderate-to-high impedance circuits the grid conduction always limits the negative excursion of the plate for any reasonable load line. This contrasts with pentodes and semiconductors which saturate for small loads. This is evident in the pentode preamplifier which has the second harmonic rising substantially later than it rises in the triode preamplifier.

THE TRIODE TUBE EMULATOR

The full triode emulation circuit, shown in *Figure* 6, has all of the needed features: grid, plate, and cathode terminals, grid-to-cathode conduction, grid-to-plate capacitance, gain, and the non-linear networks. The gain is created by two operational amplifiers such as the dual op amp, OPA2604. This operational amplifier has a sufficient gain-bandwidth product, about 10 MHz, to simulate audio tube circuits. The grid terminal drives the negative input of the first op amp to produce the needed inversion, while the second op amp creates the feedback for the first. R1 determines the proportion of distortion in the voltage gain. R2 then determines the voltage gain.

The choice of voltage gains is limited by the selection of the grid conduction components. The grid drive circuit cannot produce so much grid-to-cathode voltage that the first operational amplifier goes into negative saturation, yet a large output voltage swing is desirable. Thus, there is an engineering choice between the diode voltage drop, the power supply voltage, and the gain.

The reason why the tube emulator does not behave as its operational amplifier is that the operational amplifier is kept out of negative saturation by the grid-to-cathode diode and the positive saturation effects are not transmitted by an output resistance that becomes effectively infinite. Of course, this requires that the tube emulator plate supply be at or below the op amp saturation level.

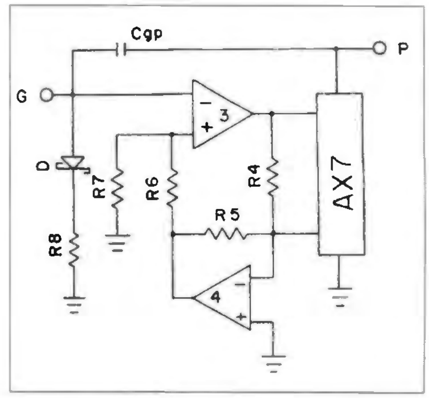

Figure 7. Low- noise Tube Emulator for a 12AX7

The low-noise implementation, shown in *Figure* 7, is viable for flat response stages. A difference between these circuits is the feedback connection between the two operational amplifiers is attenuated by R6 and R7 so that the noise of the second op amp is also attenuated. This circuit drops the noise from 3 dB over a single operational amplifier to about 1 dB higher. The restriction is that the cathode terminal is grounded. This corresponds to a cathode bypass capacitor large enough to bypass the lowest frequency of interest. This does not upset the bias since this arrangement corresponds to a bias of about 1.3 volts on a 12AX7.

The non-inverting implementation, shown in *Figure* 8, is also viable for the flat response stage. Since the amplifier is non-inverting, the diode network must have the opposite

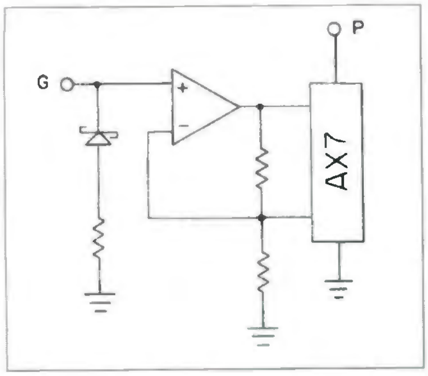

Figure 8. Non-Inverting Tube Emulator

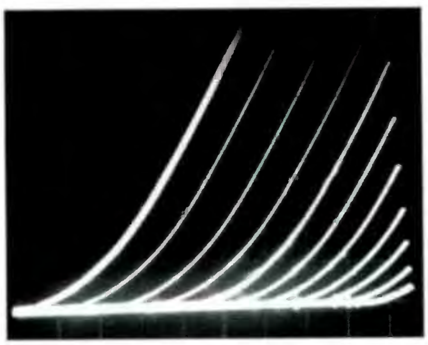

Figure 9. Output (plate) characteristics of a 12AX7 triode tube emulator:
Horz: 5 volts / div,
Vert: 0.5 milliamps / div,
Step: .05 volts

polarity and the circuit cannot use the input-to-output capacitor.

The output characteristics of the tube emulator, shown in *Figure 9*, are similar to the plate characteristics of a 12AX7 triode. The output characteristics are quite accurate around normal load lines. The inaccuracy in the region of simultaneous low currents and low voltages is not important since the emulator is not operated there. These characteristics do not resemble the current limited characteristics of pentodes nor any semiconductor.

A tube emulator was operated alongside a 12AX7 to compare output waveforms, see *Figure 10*. After adjusting the tube bias, the input and output gains and the emulator grid-to-plate capacitance, the waveforms for a variety of input levels and frequencies show a good match at various overdrives, frequencies and loads, see *Figures 11-20*. A close examination of these figures show slight differences in the curvature in some portions of some of the waveforms. This is reflected in slight differences in harmonic levels.

Harmonic analysis showed that the tube emulator erred in the direction of a more ideal tube, slightly more rounded waveforms and consequently less intense high order harmonics.

THE TUBE EMULATOR MICROPHONE PREAMPLIFIER

The complete tube emulator of *Figure 6* was used to build a microphone preamplifier, *Figure 21*, to compare harmonic structures against Russell Hamm's findings. The preamplifier is a paraphrase of a generic two-stage triode amplifier. The circuit topology is the same except for the cathode follower and is replaced by a unity gain buffer. The impedances are lowered by a factor of 10 so that the tube emulators operate at semiconductor voltages at the same currents as their tube counterparts. The biasing, however, is lower than proportional simply because that is the character of the tube emulators. After finding the appropriate biasing, the tube emulator tested like Russell Hamm's generic two-stage triode preamplifier. It did not correlate with the pentode, transistor, or operational amplifier based preamps.

The test designed by Russell Hamm is simple. The harmonic percentage for harmonics 2 through 7 are plotted against overdrive. The input level that creates 1 percent third harmonic distortion becomes the 24 dB reference level. The result for the tube emulator microphone

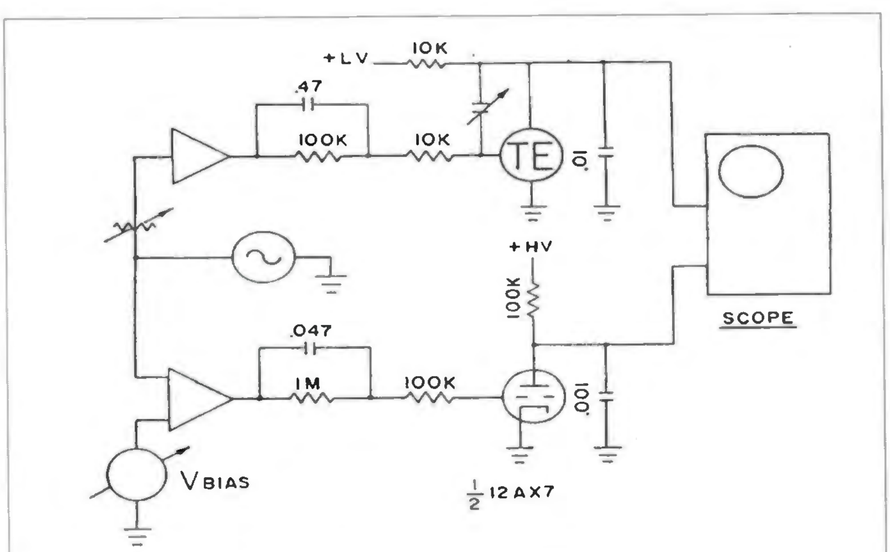

Figure 10. Comparison Tester for 12AX7 verses a Tube Emulator

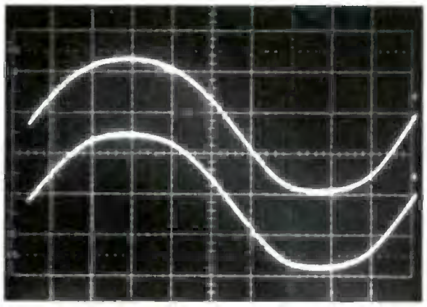

Figure 11. Output Waveform Comparison with tube at +5

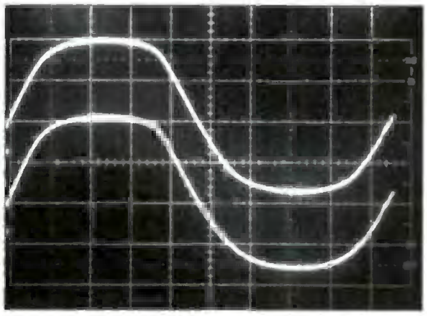

Figure 12. Output Waveform Comparison with tube at +8

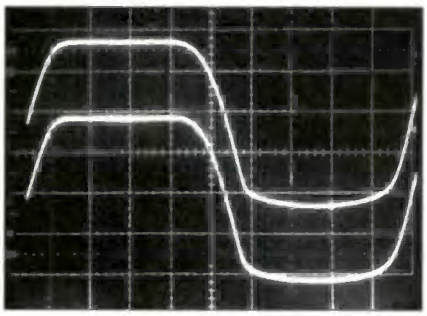

Figure 13. Output Waveform Comparison with tube at +14

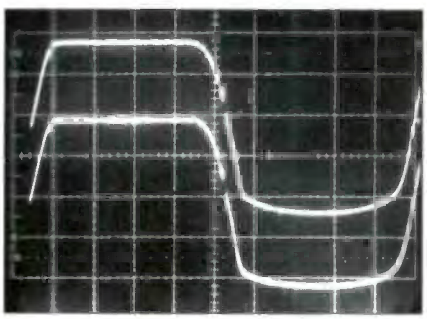

Figure 14. Output Waveform Comparison with tube at +17

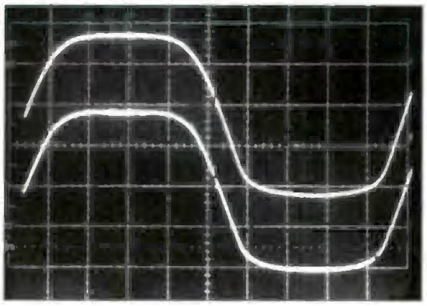

Figure 15. Output Waveform Comparison with tube at +11

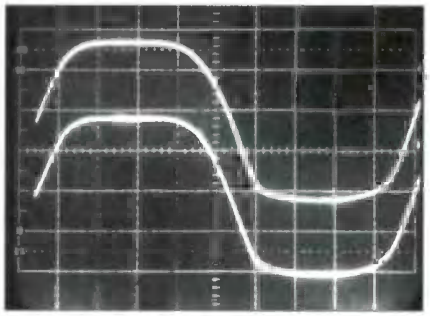

Figure 16. Output Waveform Comparison with tube at +11

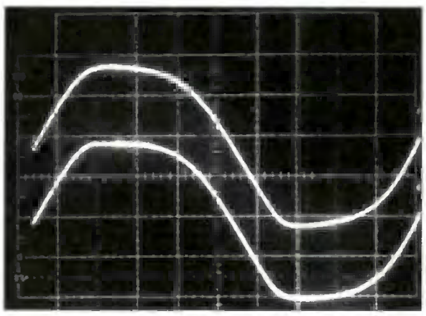

Figure 17. Output Waveform Comparison with tube at +11

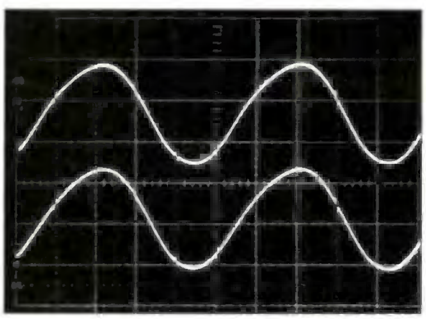

Figure 18. Output Waveform Comparison with reactive load

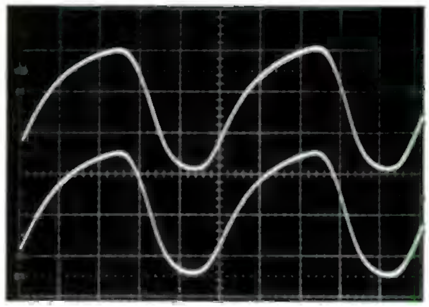

Figure 19. Output Waveform Comparison with reactive load

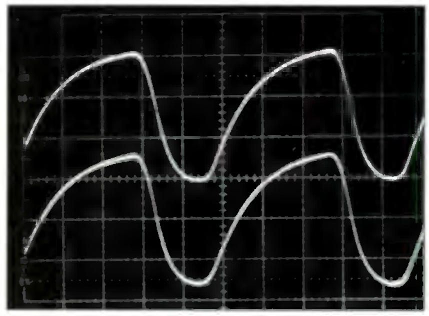

Figure 20. Output Waveform Comparison with reactive load

preamplifier is shown in *Figure 22*. The third harmonic rises first. The second harmonic rises from a lower level at the same time, then overtakes and dominates. The fourth rises about 4 decibels later than the second. The remaining harmonics remain below 5 percent, at least for 12 decibels of overdrive. This matches the description by Russell Hamm for a triode preamplifier: "The outstanding characteristic is the dominance of the second harmonic followed closely by the third. The fourth harmonic rises 3-4 dB later, running parallel to the third. The fifth, sixth, and seventh remain below 5 percent out to the 12 dB overload point" [1]. The harmonic percentage curves for the tube emu-

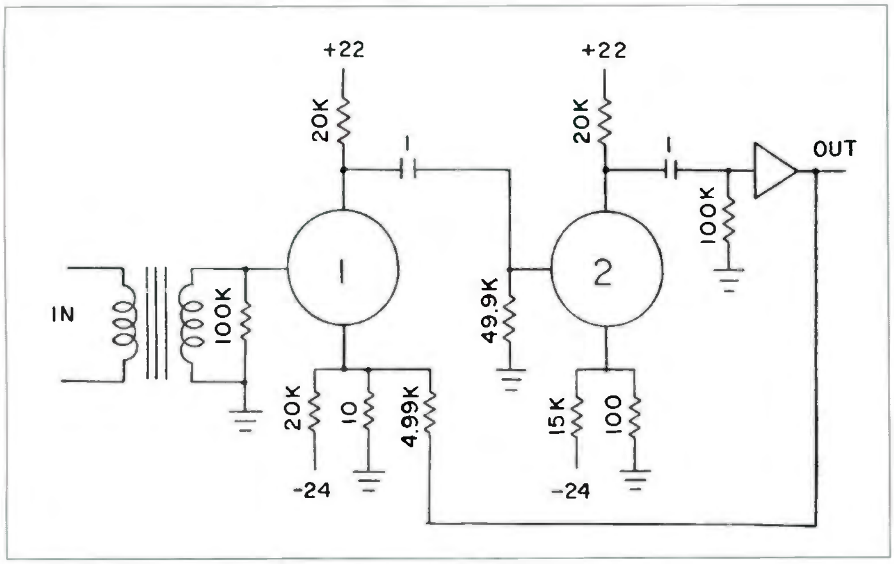

Figure 21. A microphone preamplifier using triode tube emulators.

lator and for the triode amplifiers are quite different from the curves for amplifiers made with pentodes, *Figure* 2, for transistors, *Figures* 3 and 4, and operational amplifiers, *Figure* 5. These amplifiers show a dominant third harmonic and smaller or zero even harmonic levels. Although the pentode is a tube, the second harmonic generation is delayed and smaller, certainly does not dominant. The solid state examples, *Figures 3 through* 5, also show a faster rise in the third harmonic. The operational amplifier version, *Figure* 5, has significant, rapidly rising fifth and seventh harmonics as well.

Russell Hamm did not specify which microphone preamplifiers he tested. Consequently, the only similarity between the Russell Hamm test amplifier and the source for the paraphrase of the tube emulator microphone preamplifier was that they both had two triode stages and two-stage triode amplifiers tended to be designed similarly. However, the inherent tube character is evident in both.

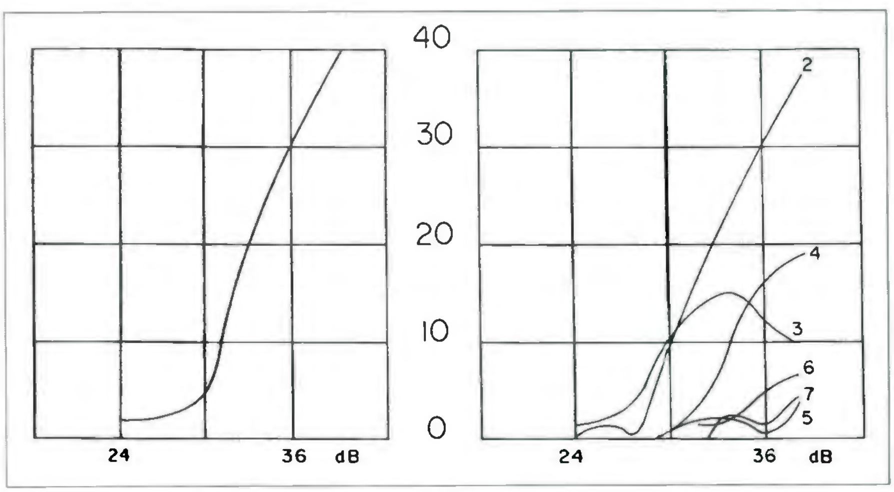

Figure 22. At left THD and at right harmonic distortion components for the tube emulator preamplifier.

The good emulation of tube microphone preamplifiers by a tube emulator preamplifier indicates that many of the professional recording classics may be recreated with tube emulators because they use two-stage preamplifiers. For example, a generic two-stage amplifier is used in Pultec equalizers and Teletronics limiter/compressors as well as microphone preamplifiers.

Just as Russell Hamm pointed to the need for tube based components [1], the tube emulator has application wherever overloads are likely: microphone preamplifiers, limiters, compressors, equalizers, and power amplifiers.

Tube emulators allow designers to easily create synergistic combinations of solid state and tube characteristics. db

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TUBE EMULATOR DEVELOPMENT

The triode tube emulator became the first because it could be tested independently, outside of a guitar amplifier, against published data. The second tube emulator with its application specific components emulate a power output stage. They translate the output of a tube emulator phase splitter to drive power MOSFETs so that they behave approximately as either 6L6s or EL34s. The third tube emulator is a low-cost triode emulator that has only the absolutely necessary essence of tube characteristics.

The triode tube emulator is a combination of non-linear networks built into an epoxy encapsulated hybrid SIP and application specific components. This SIP has 15 pins on 0.1 inch centers along its entire length and is 0.71 inches high and about 0.125 inches thick. The application specific components provide the gain elements and the grid conduction components. *Figures* 6 through 8 show various tube emulator circuits.

TUBE EMULATOR PRODUCT DEVELOPMENT

The triode and output stage tube emulators have been used in a proof-of-concept prototype guitar amplifiers. These amplifiers, a 111 watt and an 11 watt, have been received very well. The general concept and the overall tone has been accepted as tubes. The low-cost emulator has also worked quite well in its prototype guitar amplifier. The guitar amplifier makes a good test platform for the emulators because the guitar exercises the emulators in all regions.

The triode emulators have been used in microphone preamp prototypes. This preamp has the synergistic quality of dual chains, one tube emulator and the other standard solid state. This provides the user with the rich, warm tube sound or the clean, transparent solid state sound and the flick of a switch.

Additionally, the tube emulator is being built into Neumann U67 housings in a variety of circuit topologies: Neumann U67, Neumann M49, and AKG C12.

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THE TUBE MARKET

The reason for creating the tube emulator is the declining supply and quality of tubes. Although some believe that the tube supply will prevail and continue to make high quality tubes, others differ. Hartley Peavey of Peavey Electronics: "It's just a matter of time before these countries catch up to the west, and stop making cheap but reliable tubes. This is why so many companies, including Peavey, are working feverishly to create the solid state equivalent of a tube amp." [3] Paul Meisenzahl of Yamaha: "One of the big concerns for most customers is the availability of replacement tubes. No one wants to invest good money in an amp and then have to go through all sorts of trouble when the tube burns out in six months or a year." [3] Cathy Duncan of Seymour Duncan: "We do extensive computer testing on all the tubes we receive, and we send most back to the vendor." [3]

The tube market is constantly being eroded by the advance of solid state technology. New semiconductors are replacing tubes constantly.

The latest threat is the flat video display that will replace picture tubes shortly. The picture tube is 50 to 80 percent of tube markets.[4,5] Although tubes are available from former Communist Block countries, their solid state revolution should occur faster since the technology is now available from the West.

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The audio or receiving tube market has been in decline for years. The U.S. Department of Commerce Bureau of Census found that the receiving tube market dropped from $39.8 million in 1986 to $21.6 million in 1991.[3] This market segment is so small the Census is likely to stop collecting this data. The Electronic Industry Association reports a drop in imported receiving tubes from $8.3 million in 1985 to $2.67 million in 1991.[4] The receiving tubes of all types imported in 1991 numbered less than 0.77 million units.[4] This is very low. By comparison, large semiconductor manufactures do not consider manufacturing less than a million units of a single type per year.

The ever increasing capability of semiconductors is a continuing threat to the tube market. The only growth area in the tube industry has been the cathode ray or picture tube. Census data shows an increase from $911 million in 1986 to $1.415 billion in 1991. But this market is also under attack from advancing technology, the flat video display. These replacements for picture tubes will appear in television sets in two or three years. The tube industry will lose a substantial portion of its market.

The loss of the video display market plus the expected semiconductor revolution in the former Communist Block countries will accelerate the decline of audio tubes through a chain reaction. Fewer tubes will require less metal. The foundries will impose minimums, charge higher prices, and ship inferior material. Tube prices will go up and the quality will go down. Then more semiconductors will be used, etc.