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This amp design features the 6336-A power triode tube, along with push-pull class A operation, no overall feedback, low distortion, approximately 20W of output power, reliability, and high-performance sound.

BY KEES HEUVELMAN & WIM DE HAAN

One of my favorite small signal tubes is the 5687, which I have used in several designs with very good results. Its specs are outstanding and the sound is therefore really musical. The result can be a very dynamic and evolving/bold sound.

I generally use the 5687 made by General Electric, but I have also used the Philips/ECG with success. In previous applications I used a very basic grounded cathode circuit with standard values—Ra=15K and Rk=680E—and with a decoupled cathode resistor. I achieved the best results with the two systems in parallel. The 5687 tube is an easy-to-use medium-gain tube with a very low Rp. Moreover, it's lowpriced and easy obtainable.

INPUT STAGE

In this design (*Photos 1* and 2) I wished to use a different circuit as input stage. Some time ago I ordered the Tube Cad Circuit simulation program and played with it on many occasions. This tool provides many interesting details, including circuits, one of which is the so-called current sourced grounded cathode amplifier. In this circuit the plate resistor is replaced with a triodebased current source, which results in more gain and better PSRR.

According to Tube Cad, each triode exhibits a certain amount of transcon-

ductance, which is the degree to which the flow of current through the device changes as a response to a change in grid voltage relative to the cathode. By dividing the idle current by the transconductance, an input overload voltage results (Vth). If this Vth voltage is exceeded in a negatively charged way relative to the cathode voltage, the tube stops conducting any current. This voltage serves as a rough figure of merit for a tube circuit, as the higher the value, usually the better the sound. Because this Vth is much higher than in my standard grounded cathode circuit, I chose this circuit. The basic idea for the circuit is shown in *Fig. 1*.

In other applications I noticed that a mu-follower (looks quite similar to

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REVELT AGAINST THE SOLD STATE



WHERE THE TUBES OF THE WORLD UNITE.



the used circuit) with the signal taken from bottom triode anode sounded surprisingly better than if taken from the cathode of the upper triode—this was confirmed by several other hobbyists. The relatively high output impedance of the circuit is less important, because the following driver stage will have a high input-impedance.

Throughout this amplifier, I used WIMA FKP caps as coupling capacitors. These low-priced capacitors give very good sonic results. Feel free to use more "dedicated" audio capacitors such as Hovland, MIT, or Jensen, which I've used before, but this time I stayed with the FKPs.

PHASE SPLITTER

I chose a long-tail circuit as phase splitter/driver stage. This widely used circuit yields fair gain and fair balance—it is perfect for the job. In this application I chose the 6SN7 in a configuration with a current source, which I built around a small transistor with



In the original concept the current source was intended to be connected to a negative voltage. However, to keep things simple, and because of good results with the prototype, I built the final amplifier without using this option. Reference voltage is taken from the main high-voltage supply using a simple resistor.

The 5687 input circuit and the 6SN7-based phase splitter yield enough gain to make the overall circuit work without overall feedback. Because of the relatively low gain, feedback is not possible using this configuration, though one of the design goals was no use of overall feedback. Overall gain/ sensitivity of the design is about 20dB, which is a good figure.



OUTPUT STAGE

In searching for the perfect output tube, I discovered that initially the choice was more difficult than expected. The transmitter tubes are not my choice; I consider the very high voltages a problem. The 300B tube is out-of-budget, and, for example, a 50C-A10 is expensive and rare. The 6AS7/6080 is an option. However, after listening to a 6336-Abased amplifier and knowing that I had several of them somewhere in a shoebox, I made my choice just like that.

The 6336-A tube is intended for power supply use and contains two separate triode systems (Fig. 2). Mu is as low as 2 and power consumption is as high as 5A at 6.3V; maximum plate dissipation is 30W. Because plate resistance is very low, the 6336-A tube can be used in output transformerless (OTL) circuits. Another choice is the 6528, which is very similar to the 6336-A, but mu is 9. This would make it easier to drive, though this tube is very rare. Strangely enough, not too many circuits can be found using the 6336-A-not on the net, in magazines, or other publications. However, I know that Luxman designed a pushpull amplifier (the KMQ80) using the 6336-A; unfortunately I was unable to obtain a copy of the circuit diagram.

I used the 6336-A in full class-A using cathode bias. It would work perfectly well with low primary impedance to yield high output power; however, my goal was for a high 8k load for low-distortion figures with less output power. Output power is less important.

Because output transformers are sensitive to DC unbalance, I added a small meter and a variable resistor to





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the cathode circuit to solve this problem. Selecting the 6336-A for balance would be impossible to do. This circuit is optimized for toroidal output transformers, such as those manufactured by Amplimo/Plitron.

Due to the high transconductance, cathode bias is the only option. Negative bias will not give the 6336-A the stability it needs. In my attempts to use negative bias, I had no good results. With cathode bias, the 6336-A worked without problems and stability was excellent.

You must take special care with the cathode resistors of the 6336-A. The high bias voltage and current will produce enormous heat; each resistor will need to dissipate more than 7W. Because of the class-A operation, the 6336-A becomes really hot, so preheating the tube for some minutes before switching the main high-voltage is necessary.

BIASING THE 6336-A

In the original concept, the 6336-A was intended to dissipate around 25W.

Using the tube's Chatham datasheet, I selected a 1450 Ω resistor for biasing the 6336-A, thus using an effective anode voltage of 335V (power supply, cathode bias). In this case, bias voltage would be around 114V; bias current would be approximately 70–80mA.

The prototype used two 680Ω resistors in series as cathode resistors; balancing was done with a tandem 100Ω potentiometer (*Fig. 3*). Because these are hard to find, I chose the configuration as drawn in the final circuit (*Fig. 4*).

In the final design, the mains transformer has an option for four secondary windings: 320V, 330V, 340V, and 350V. I set the high voltage using the 320V winding, yielding a +410V DC voltage with all loads attached. The amplifier worked very well and beyond all expectations. Bias voltage is around 100V, giving a 70mA bias current per triode.

Because of the high bias voltage and current, the bias resistors dissipate a serious amount of heat. Beware of this! In *Photo 3* and *Fig. 5* you can see how to "implant" the 25W resistors. The 2mm aluminum main chassis is used as a heatsink; the eight 25W resistors are mounted on an aluminum u-bar that is affixed to the chassis. Airflow should be more than adequate; but you might consider installing a small fan just to keep the air flowing. I chose



FIGURE 3: Alternative output circuit 6336-A using a tandem 100Ω potentiometer.



6221 S Maple Ave Tempe Arizona 85283 480.820.5411 fax: 480.820.4643 or 800.706.6789 www.tubesandmore.com e-mail: info@tubesandmore.com For Distributors, Resellers and Manufacturers 800.840.0330 or 480.755.4712 fax: 480.820.4643 www.cedist.com e-mail: info@cedist.com the 25W rating to give the amplifier its reliability; 12W resistors would work fine in this case, though these heatsinked 25W resistors are bulletproof (*Photo 4*).

Some readers may wonder about the connection of the cathode bypass capacitors of the 6336-A tube. The configuration acts like a push-pull stage with one common cathode resistor without bypass. The two separate cathode resistors provide DC stability for the 6336-A. Its DC performance is very stable and therefore very reliable.

The 6336-A has relatively high distortion figures. Using a high load impedance and with bypass capacitors as shown in the circuit, the 6336-A shows very low distortion figures (0.12% at 1W/1kHz). The bypass capacitors are used for AC coupling. I found distortion to be lower than if each cathode resistor had its own capacitor directly connected to ground. You notice this clearly when the amp is driven into its limits.

OPTIONAL DRIVER STAGE

The 6336-A tube turns out to be a difficult load for the long-tail circuit. Measuring the prototype, I encountered a high rolloff at 70kHz. The output transformer specs show something different, so the circuit must be the limiting factor. The toroidal transformer shows a high cutoff re-



sponse of 130kHz. With an additional driver stage—a cathode follower using a 6SN7—the amplifier measured up to as high as 130kHz (-3dB). I located the cause and solved the problem. However, I built the final amplifier without use of this circuit. I chose simplicity instead. The final amplifier measures up to 70kHz, which is still a very good figure.

OUTPUT TRANSFORMER

In previous projects I used Hammond and Audio Note transformers, both with good results; though in this project I chose a toroidal output transformer made by Amplimo—the VDV 8020. The primary impedance of this toroidal transformer is $8k\Omega$ and is intended for EL84 push-pull use. Frequency response is exceptional with -3dB points at 2Hz and 134kHz; power rating is 20W.

This good performance is due to an extremely high coupling factor, very low leakage inductances, low internal capacitances, and no conflicting resonances below 100kHz. This is achieved through the use of multi-sectioned windings together with special combinations of series and parallel connections. The multi-segment secondary winding has a 5Ω impedance, suitable for both 4 and 8Ω loudspeakers.

In 1993, Amplimo (the Netherlands) was the first company to supply toroidal output transformers with a

> quality factor (synonymous with frequency range) greater than 290,000. Plitron distributes these toroidal transformers in the US and Canada. An alternative transformer is the Hammond 1650 F (7K6/25W), which is a great value for your money.

ADJUSTMENTS

The sections of the 6SN7 used in the long tail are not equal, so I added P1, which should be adjusted in such a way that the AC voltages of the two



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anodes of the 6SN7 systems are equal. You might attach a 1kHz test signal to the input of the amp and measure the anodes for AC voltage. If not, turn P1 to the point where the voltages are equal. This completes the adjustment.

The current source of the long tail is set by P2. You should adjust it in such

a way that voltage measured at the cathodes of the 6SN7 is approximately +8V (this will rise to approximately 9.6V at +450V PSU). If you can obtain a distortion analyzer, try to adjust the output distortion to a minimum, again, using P2.

The DC unbalance in the output



stage should be adjustable, because selecting the 6336-A for balance would be impossible to do. I added P3 and adjusted it so that the meter M1 is exactly in the middle. Voltage across the meter is zero, because the measured voltages across resistor R20 and R21 are equal. So current through one-half of the 6336-A is equal to the other. With some output transformers, this unbalance is not as important; however, toroidal output transformers are very sensitive for this DC unbalance. With the circuit as shown, unbalance can be less than 1mA.

I used a low-cost analog tuning device, which is intended for "tuning" FM tuners (*Photo 5*). Sensitivity should be 50 or 100μ A, so adjustment is done easily in this way. R20 and R21 should be $\pm 1\%$ or better.

Trying several 6336-A tubes, I noticed that the RCA and Tung Sol yielded low distortion and high output. The Cetron measures worse. The Raytheon is adequate if the cathode de-coupling capacitors are connected as shown in *Fig. 5*.



SPECIFICATIONS

0.07% distortion at 1W/1kHz. 17W into 5Ω at 1% distortion.

F (-3dB) = 2Hz - 70kHz; with additional 6SN7 cathode follower circuit up to 130kHz.

All measurements using a Tung Sol 6336-A output tube, circuit set to +450V DC.

POWER SUPPLY SUGGESTION

The high-voltage supply is straightforward, with no particular precautions to consider (Fig. 2). However, heater supply should be left floating or should be related to +150V; otherwise, the 5687 heater-to-cathode voltage will exceed its maximum value. This applies also to the 6SN7 as used in the optional cathode follower. Another option is connecting the secondary winding with a capacitor to ground. Be careful with the 5687 and the 6336-A, which draw together almost 6A of heater current.

The final amplifier uses a custommade power transformer with several secondary windings; however, DC voltage should not exceed +450V. If so, capacitors C1 and C2 will become overloaded and the 6336-A will be pushed to its limits or, even worse, exceed its maximum rating. During power-up the tubes are not conducting yet, so high voltage during this period could exceed the maximum rating of the capacitors. Please be aware of this. Pre-heating the tubes for several minutes should be mandatory (especially the output tubes), and in this case powering-up should be no problem using the 500V-rated capacitors.

A FINAL WORD

The amplifier shows very low distortion figures, but the drawback is the amount of heat and low efficiency. This design is not too complicated nor too difficult to build, though you need to pay attention to details—for example, the bias resistors, because heat circulates around the 6336-A output tubes. This amplifier is very reliable; it's worked for over eight months without any problems or additional adjustments.

The sound is very open and sound stage is extremely good. Bass is outstanding—dry, punchy, bold, and very precise. Amazingly enough it combines very well with my DIY low sensitivity, low impedance Dynaudio speakers (a Dynaudio Craft look-alike). Keith Jarrett's *At the Blue Note* is reproduced in an excellent and astonishing way; drums, bass, and piano are so alive. Barry White's opening track from the *Staying Power* CD sounds even more involving.

Tuck & Patty's "Friends in High Places" from *Dream* is a difficult task for many systems, though it is reproduced in a way you like it to be. Music is really dynamic—no stress. You forget all about the electronics.

One of my favorite works for solo piano, Cesar Franck's Prelude, Chorale et Fugue played by Russian pianist Evelina Vorontsova, is reproduced in an astonishing way. All drama, emotions, and virtuosity of this pianist can be felt. Also, I've been using the

SOURCES

TubeCad/GlassWare

www.tubecad.com **Amplimo Toroidal Transformers** www.amplimo.nl (distributor for Europe) **Plitron Toroidal Transformers** www.plitron.com (distributor for the US and Canada) **Circuits drawn with sPlan 3.0** www.abacom-online.de

FOR ADDITIONAL HELP

Web: www.wdehaan.demon.nl/ E-mail: wim@wdehaan.demon.nl

- RCA 6336-A at 1W: 0.12% distortion with cathode de-coupling capacitors connected as used in circuit; 0.06% with cathode de-coupling capacitors connected directly to ground.
- RCA 6336-A at 10W: 0.65% distortion caps as in circuit; 0.88% caps to ground.
- Cetron 6336-B at 1W: 0.12% distortion caps as in circuit; 0.1% caps to ground.

• Cetron 6336-B at 10W: 0.1% distortion caps as in circuit; 1.45% caps to ground.

• Raytheon 6336-A at 1W: 0.07% distortion caps as in circuit; 0.27% caps to ground.

• Raytheon 6336-A at 10W: 0.6% distortion caps as in circuit; 1.6% caps to ground.

• Tung Sol 6336-A at 1W: 0.07% distortion caps as in circuit; 0.12% caps to ground.

• Tung Sol 6336-A at 10W: 0.4% distortion caps as in circuit; 0.75% caps to ground.





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Dynaudio Esotar tweeters for the last ten years or so, and still they come up now and then with a new secret, which is now revealed by this 6336-A-based amp.

Again, using triodes only, no feedback and an output tube that's not intended for audio use, it is possible to build an amplifier with good specs and good sound, combined with reliability and sustainability. 🔳

ABOUT THE AUTHORS ...

Kees Heuvelman is a retired engineer and technician with much knowledge of tube theory, schematics, and applications. He has designed dozens of tube amplifiers using the EL34, 6550, KT88, 5998, and 300B. He is also a great admirer of composers such as Beethoven and Mahler.

Wim de Haan is a medical engineer and technician interested in audio electronics. His original projects included DA converters, (active) loudspeakers, tube amplifiers, and hybrid amplifiers. Most of all he is a music lover-from John Scofield to Café del Mar to Keith Jarrett—and he is really into classical piano music.

EQUIPMENT USED

Distortion analyzer: Hewlett-Packard HP 333A AC true RMS voltmeter: Philips PM 2454B Generator: ELV SG 1000 audio low distortion generator Oscilloscope: Philips PM 3211

PARTS LIST: SUGGESTED POWER SUPPLY

| R1, R2, R3, R4 | 1k/2W |
|--------------------------------------|--|
| C1-C2, C3-C4 | $2 \times 47 \mu F / 500V$ |
| C5, C6, C7, C8 | $47\mu F/500V$ |
| D1-D4, D5-D8 | 4× BY448 (silicon diode 1500V/4A20ns or equivalent) |
| L1, L2 | Choke 10H/200mA |
| TR1 0 - 320 + 0 - 320 (350mA + | //330V/340V/350V //330V/340V/350V 350mA) |

TR2 6V + 6V (120VA)

AMPLIFIER PARTS LIST

| R1 | 470k |
|--------------|-----------|
| R2, R15, R19 | 1k |
| R3 | 1M |
| R4, R6, R11 | 680E |
| R5 | 15k/3W |
| R7, R8 | 120k/2W |
| R9 | 680k |
| R10 | 180k/3W |
| R12, R16 | 1k** |
| R13, R17 | 68k/2W** |
| R14, R18 | 390k |
| R20, R21 | 22E/1% |
| R22, R26 | 3k3/25W* |
| R23, R27 | 2k2/25W * |
| R24 | 15k |
| R25 | 1k/3W |
| R28 | 370Ω |
| | |

[220E/2W in series with 150E/2W]

All resistors 600mW, unless otherwise specified.

* Resistor on heatsink.

** Only to be used with additional circuitry.

| P1 | 22k/1W |
|------------|-------------------------|
| P2 | 500E/0.5W |
| P3 | 1k/5W |
| C1 | 100nF/200V |
| C2, C3 | 47nF/1200V |
| C4, C6, C7 | 100nF/400V |
| C5 | 470μF/16V |
| C8, C9 | 220μF/200V |
| TI | BC107B or equivalent |
| D1, D2 | LED green 5mm |
| V1 | 5687 |
| V2 | 6SN7 |
| V3 | 6SN7** |
| V4 | 6336A |

** Only to be used with additional circuitry.

- M1 100µA-0-100µA
- TR1 Output transformer 8k/20W (Amplimo VDV8020PP or equivalent)

GLASS AUDIO •

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Reducing Filamentary Triode Amp Distortion

After all these years, can there possibly be anything new in vacuum tube technology? Maybe.

By Larry Lisle

I've discovered that it's possible to dramatically reduce the intermodulation distortion in class A filamentary triode tubes by reducing the filament voltage. If this has been noted before, I'm not aware of it.

Before members of the "Society for the Preservation of Olde Tubes" start putting their quills to parchment, let me say that this is experimental. For the sake of tube life, I recommend only a moderate reduction in filament voltage and the use of lower-than-normal signal voltage until we know more.

THE THEORY

I believe the most important reason for the drop in distortion with the lowering of filament voltage is the reduction of the space charge. This makes the potential distribution across the tube more linear. The space charge is the cloud of electrons that usually surrounds the filament (or cathode) of a vacuum tube. Some of these electrons are drawn away to the grid/plate system, but others remain in the vicinity of the cathode and actually can repel some electrons, forcing them back to the filament.

You'll find a good explanation of this in *Fundamentals of Radio-Valve Technique*, by J. Deketh¹. *Figure 1*, from page 18 of the text, shows how the potential distribution across the tube becomes linear without the space charge and how all the electrons go directly to the grid/plate. Reducing the voltage below the point where the space charge disappears or operating the tube at too high a signal level can damage the filament.

THE DATA

I first noticed this drop in distortion when I accidentally reduced the filament voltage while making intermodulation tests on an amplifier using a 71A. I thought perhaps there might be some peculiarity about the 71A, the battery bias I was using, or the DC on the filaments. So I repeated the test using a 2A3 with self-bias and the



FIGURE 1: This diagram is from Fundamentals of Radio-Valve Technique, by J. Deketh. It clearly shows the change caused by the reduction of the space charge.



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standard 750 Ω resistor, and a bypass capacitor and AC on the filament. The results were similar.

I had been using the standard SMPTE method with frequencies of 60Hz and 6kHz at a voltage ratio of 4:1. I thought perhaps one frequency or the other was somehow being attenuated, so I repeated the test using the CCIF method. I used frequencies of 15kHz and 16kHz and measured the 1kHz difference, which was almost identical to the results obtained with the SMPTE method.

To be certain, I repeated the test with frequencies of 5kHz and 6kHz. Again, there was a marked drop in intermodulation distortion to a minimum value of about 7.8% of what it had been with the standard filament voltage of 2.5V. The SMPTE method produced about 12.3%. Please note: Results will vary, even with tubes of the same type, and even the same tube will result in different numbers as it ages.

Other components in the circuit, such as the output transformer, also have an influence. The test conditions are important, too. Filament voltage is only an indicator of emission, which is proportional to filament temperature. There is a time lag between setting a filament voltage and stable emission at that temperature. Taking readings as the filament voltage is increased will be slightly different from taking readings as the voltage is decreased, unless

3.5

2.5

3

2

1.5

1

0.5

0

0

considerations.

2

FILAMENT VOLTAGE 71A

FIGURE 2: Intermodulation distortion as

a function of filament voltage for a 71A.

These curves were made at low power out-

put but results are similar at higher power.

See the text for cautions about tube life

INTERMODULATION DISTORTION

you allow enough between time measurements.

I proceeded to experiment with different tubes. and did limited tests on the 30, 71A, 45, and 211 with the same reduction in distortion, although in different amounts different and percentages of the normal filament voltage. I didn't measure the 211 below the point where the space

charge disappeared, nor did I test above a small signal level (211s are becoming too expensive).

I made extensive measurements with RCA 2A3s using two sets of parameters. In the first, the plate voltage and power output were held constant. This would represent a situation in which a new amplifier was designed for a given output and plate voltage. In this case the plate current dropped as the filament voltage went down, while the input signal had to be increased to compensate for the reduction in gain.

These changes were slight until the space charge was exhausted and then increased rapidly. Seeing either of these in practice is a sign to raise the filament voltage to a safe level.

In the second parameter, the input signal voltage was held constant and the other operating conditions were free to change. This is like taking an already operating amplifier and simply reducing the filament voltage. The plate current will drop, the plate voltage will rise slightly, and the output power will go down. Again, seeing a greatly increased rate of change in any of these is a signal to increase the filament voltage. Distortion versus filament volt-

· Series1

6

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4



9

NTERMODULATION 8 7 DISTORTION 6 5 · Series1 4 3 2 1 0 0 1 2 3 **FILAMENT VOLTAGE 45** FIGURE 3: IM distortion as a function of filament voltage for a 45.

age curves were almost identical with

To be sure the intermodulation dis-

the different parameters.





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not about one specific amplifier but a general presentation of the reduction of intermodulation by adjusting the filament voltage.

An alternative explanation crossed my mind. Could the reduction of distortion be caused by increased resistance in the cathode circuit, producing negative feedback, similar to that of an unbypassed cathode resistor? To check this I tested a 2A3 without a bypass capacitor and with a variety of resistors between the center-tap of the filament transformer and ground. Intermodulation distortion reduction could be achieved, but not as great as with the lowering of filament voltage. Also, the output fell considerably more.

In addition, I checked the 2nd and 3rd harmonic output while lowering the filament voltage. The decrease in 2nd harmonic distortion corresponded to the reduction in IM distortion, as could be expected since the distortion of triodes is primarily 2nd order. However, the 3rd harmonic distortion, although very low, increased slightly.



If the lowering of distortion was due to negative feedback, both 2nd and 3rd harmonic distortion could be expected to decrease.

DOWNSIDES

The first is signal level. To minimize shortening of the life of the filament, I don't recommend this technique at the normal output level of a tube. I suggest that with a 2A3, for instance, the music peaks probably shouldn't exceed 1W very often. Because of the logarithmic nature of the ear and the fact that most of the music is below that, you might not even notice the difference². Remember, this is experimental.

The second downside is the question



of tube life with reduced filament voltage regardless of signal level. Robert Tomer, author of Getting The Most Out of Vacuum Tubes³, says, "A voltage under the rated value on the other hand, while having some disadvantages as far as other characteristics go, tends to increase heater life substantially." Other authorities disagree.

I'm not sure there's enough data available to make a definitive statement. The days when you could take a hundred 2A3s off the line and measure tube life against filament voltage are over! Perhaps readers can report their results through audioXpress. I wouldn't recommend trying unused new-old-stock (NOS) tubes, both from the standpoint of cost and also because the extra emission of new tubes may give misleading readings until they age a bit. I also wouldn't try this with very expensive tubes such as Western Electric 300-Bs until we have more information.

Third, finding the best operating point requires some test equipment, at least enough to measure filament voltage and plate current. But anyone using tubes really should have a way of measuring these, especially filament voltage. Line voltage is considerably higher in many areas than it was during the tube era, and you may be surprised to find that your 6.3V tubes are being subjected to well above 7V. This will definitely shorten tube life!

I suggest not going below 80% of the rated filament voltage without means of measuring either intermodulation distortion (preferred) or 2nd harmonic distortion or THD. I think the best course is to reduce the filament voltage to a value above the point of absolute minimum distortion. This will give a safe margin to compensate for loss of emission as the tube ages, fluctuation in line voltage, and so on, but still give a significant reduction in IM distortion.

Finally, a separate source of filament voltage for only the output tube is required. However, a separate filament transformer for triode output tubes is often used anyway, because they often require different voltage than the usual 6.3V tubes used elsewhere in the amplifier.

Lowering the intermodulation distortion produced in filamentary triode tubes through control of the filament voltage may prove to be a very useful technique. Ît may be used for voltage amplifiers or for output tubes at reduced levels. I've never seen anything about it in print and would welcome any information to the contrary. While it may not be needed in some amplifiers, it may prove to be a valuable alternative to negative feedback or cancellation in reducing distortion.

REFERENCES

1. Reprinted by Audio Amateur Press, (603) 924-9464, custserv@audioXpress. com, ISBN 1-882580-23-0, \$29.95.

2. A 2A3 is rated in the manuals as putting out 31/2W at 5% distortion. This doesn't include transformer losses, the voltage reduction from using self bigs, and so on. The restriction to 1W on peaks probably represents only a 3 or 4dB actual decrease.

3. Also from Audio Amateur Press, ISBN 1-882580-29X, \$14.95.



The Many Faces of Distortion

A look at the various types of distortion and the results of an interesting experiment involving counter-Electro-Magnetic force (EMF).

By Jean Hiraga

(Translated by Jan Didden²)

Distortion in audio, defined as a lack of fidelity with respect to a reference, applies to an amplifier when the output signal the amplifier delivers is not exactly the same as the signal applied to the input. Even if it is possible to classify it in different categories, distortion remains difficult to recognize "in the field," in the presence of a music signal.

Since the birth of the first amplifier circuits for low-frequency applications, designers have searched to battle all forms of distortion which lead to a deformation of the signal to be reproduced. Basically, distortion can be subdivided into many dozens of categories, one of which is the type known as "nonlinear," or "amplitude distortion." This, in turn, exists in different forms: amplitude-frequency nonlinearity, harmonic distortion, intermodulation distortion (which is produced when the amplifier is presented with two or more signals simultaneously), transient distortion, phase distor-

tion, frequency distortion (where the amplification factor is not constant over frequency), and scaling distortion (which arises when the amplification factor varies with signal amplitude).

In the case of the power amplifier, these various types of distortion intertwine themselves with those produced by the loudspeaker driver and the speaker acoustic enclosure, and their association can give rise to other



amplifier stability problems or even re-inject into the amplifier as a "Counter-Electro Magnetic Force" (CEMF) signal sent back by the loudspeaker. We will look at it later.

STEADY-STATE AND TRANSIENT HARMONIC DISTORTION

We speak of harmonic distortion if an amplifier generates-as a result of a signal to be amplified, for example a 1kHz sine—one or more harmonics of even or odd order of a certain level: 2kHz, 3kHz, 4kHz, 5kHz, 10kHz. This form of distortion will

more or less strongly alter the original signal and its harmonic envelope and will produce timbre changes that have been the subject of attempts to evaluate, quantify, and classify since the beginning of electroacoustics.

To speak about harmonic distortion is also to speak about harmonic sounds and dissonances, much of the basics that have given music its famous chromatic range made up from the 12 notes in the tempered range. Our sensitivity to consonant and dissonant sounds merits some explanation. In the case of light and vision, the mix



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of blue and yellow produces a kind of harmonic result-green-which, in isolation, no longer allows you to discern the original components, yellow and blue.

Our perceptive system for sound functions quite differently. If you play two notes simultaneously on a piano—a "do" and a "sol"—vou hear the two tones as a harmonic fusion while still being able to discern the two. The color "white" can be considered as such

a perfect harmonic mixture of the seven colors of the rainbow that our eyes are unable to discern the components. Even if this example is applicable for light and vision, it is not at all the same in the case of sound.

White noise—a very complex sound that you could transpose into white light-is not audibly perceived as a perfect fusion of myriad pure tones. It is actually perceived as a great number of tones, a diversity of sounds giving the impression of being badly mixed.

This extraordinary capacity of the ear to analyze a sound as complex as white noise proves the fact that these tones-however close or numerous they are—are not sufficient to fuse into a single and unique sound, and impossible to generate so that you could baptize it "white sound." It is the German Georg S. Ohm (1789-1854), a physicist, to whom we owe the fundamental laws of electrical current and also the contribution of this fundamental faculty of the ear known as "Ohm's law of acoustics."

HARMONIC SOUNDS, **DISSONANT SOUNDS**

The study of harmonic sounds and dissonant sounds goes back many centuries. Interested readers should avail themselves of the works of Zarlin (Italy,



FIGURE 2: Interface Inter-Modulation distortion test under load conditions, designed to simulate the occurrence of a signal generated by the speaker counter-EMF, fed back into the amplifier.



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A431S a reproduction of the Dynaco A431 output transformer as used on

the MkII and MkIII amplifiers and Sunn guitar/bass amplifiers.

Other stuff we're working on: A420 (6600 ohm 30W) and C354 Exact replacement for chokes in ST70, Mk2, Mk3 and Mk4 A442 (4300 ohm 60W with tertiary screen winding)...

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works of Herrmann von Helmholz

published in 1862 under the title On

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tract a fundamental characteristic of

our auditory perception system: the

degree to which intervals within an

octave are harmonic or dissonant. We

also owe a debt of gratitude to other

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by Bruce Rozenblit

Explains what vacuum

them. Gives you the

tubes do and how to use

complete picture of tube

audio design including

chapters on stabilization

and testing, how to work

effectively as a designer,

classic amps and preamps.

and descriptions of 13

Tips on construction

components and tubes

tools and choosing

are included.

16th century), the author of the "Zarlin Scale," also called "the physicists scale" or diatonic scale; the discussions and research with regard to the tempered scale and the exact pitch of the twelve tones of which it is composed; the work of Marin Mersenne, the author of a famous piece titled "The universal harmony"; or the often quoted



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researchers such as Fletcher, Zwicker, S. S. Stevens, and Steinberg, whose important work deals with frequency differences between pure tones and their degree of consonance or dissonance. This research greatly facilitates the study of the subjective influence of harmonic distortion generated by an amplifier.

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We are especially indebted to two researchers, Wegel and Lane, for an important basic study from 1930 on the analysis of amplifier harmonic distortion and its subjective influence. These scientists determined with great precision the respective level of each harmonic enabling us to perceive-thanks to the effects of successive masking and multiple harmonics-the illusion of a pure tone devoid of any harmonic distortion. They concluded that for a fundamental of 400Hz, heard at a level of 76dB SPL, the 2nd, 3rd, and 4th harmonics need to have a level of 61dB, 58dB, and 50dB to be audible.

The means available at that time did not allow analysis of harmonic levels of higher order. These experiments could only be realized from 1960, at which time it was shown that for harmonics of order 15 to 20, these harmonics play a role even at levels less than 0.0008% of the total emitted acoustic energy! Together, these well-executed studies allow us to understand why amplifiers, however perfect they may appear in measurements, still produce

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large distortion, and specifically a very unstable form of distortion because it results from a signal that essentially consists of musical transients. It also explains why certain tube amplifiers (but not all, far from it!) or some transistorized amplifiers reproduce very beautiful, very harmonic sound.

However, these findings must be taken in context. Consider the fact that both an amplifier and a loudspeaker consist of several stages connected in series and also in loops. Each of these stages gives rise to its own specific type of distortion which is fused with that of the other stages, thus forming a global system that is impossible to comprehend in the lab once the sinusoidal signal is replaced by music.

"SOFT" AND "HARD" DISTORTION *Figures A* through *D* show a few characteristic examples of harmonic distortion as a function of output power for three basic frequencies covering almost the complete audio band, namely, 40Hz, 1kHz, and 10kHz. Curve A, called "soft" distortion, is often found among amplifiers lacking feedback. You can recognize it by a distortion level which is not very small, but increases in a very regular way as a function of the increase in power output.

The best among them have the advantage of producing the same distortion at the same power level over much of the audio frequency band. The majority of the amplifiers that produce this "soft" distortion also show "soft" clipping. When clipping a sinusoidal signal it becomes a curve whose peaks are not cut off but only lightly flattened, which makes the onset of saturation much less audible. The curve in Fig. B, called "hard" distortion, which is more common, generally results from a high level of feedback. The harmonic distortion level is low or even very low over most of the audio band.

Harmonic distortion rises when the level approaches the saturation point, the peaks of a sinusoidal signal almost always forming a flat, cut-off shape, generating higher order harmonics and a very objectionable sound. Curve C corresponds to an amplifier in which the nonlinearities cause an increase or a decrease in harmonic distortion levels at certain frequencies and certain power levels. You may find this (but not always) in circuits equipped with power MOSFET transistors, active components whose known disadvantage is the high input capacitance. You can also find it in hybrid topologies in which the distortion generated by one stage is partially compensated by the distortion of another stage, of which the audible quality varies case by case. You'll find curve D in any type of amplifier, tube, transistor, or hybrid. It results in distortion levels much higher at higher frequencies, which can, in many cases, produce a sound that is hard, gritty, or objectionable.

SUPPLY INSTABILITIES

The majority of amplifiers rely on a basic supply circuit, consisting of a supply transformer with one or two secondary windings connected to rectifier circuitry followed by a capacitor filter or by RC or LC pi-filters. Because



the supply is usually common to both channels and connected to each stage forming an amplifier channel, the input of a signal to the amplifier being amplified stage by stage has the secondary effect of generating a myriad of different current draws, shifted in phase or delayed, which will be combined with secondary effects related to different phenomena and to several components, such as:

• various inertias related to charge and discharge times of the filter capacitors

• transient behavior of the supply transformer, the rectifier diodes, and mains filters

FIGURE A: Soft distortion. Often found in equipment without feedback.

FIGURE B: Hard distortion. The classical case, with a rapid rise near the saturation point.

FIGURE C: Irregular distortion. Due to partial cancellation of the distortion at certain power levels.

FIGURE D: High-frequency distortion. Similar to *Fig. B*, but with higher distortion at higher frequencies.



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• variations in the magnetic field emitted by the supply transformer and possible influences on the audio circuits

• irregular behavior of the supply if frequencies directly related to the mains frequency (for example, 50Hz, 100Hz, 150Hz) are being amplified

• Rattle-like phenomena, resulting from a cascade of transient signals (high-level impulses) that leave residual instabilities

• sagging, often very strongly, of the supply voltage in a loaded state (which

could reach 50V in badly stabilized tube amplifiers), with the severe consequence of an instability in the different operating points of each amplification stage followed by inertia phenomena related to the charging time of the filter capacitors.



FIGURE 3: Comparative spectral analysis of amplifiers subjected to the transitory IIM distortion under load conditions shown in Fig. 2.

- a. Curve 1: Original composite signal with its two components at 50Hz and 1kHz;
- b. Curve 2: Output signal of an amplifier presenting a very good performance at this test;
- c. *Curve 3*: Output signal of an amplifier with excellent classical test results for harmonic and IM distortion (less than 0.008% at half power over most of the audio band), but showing strong instabilities in this test, which could be the cause for its "unexplainable" displeasing sound;
- d. *Curve 4*: Output signal of the same amplifier as in *Curve 3*, but at higher power. We see that the nature of the instabilities has increased and changed, predicting unstable behavior at other power levels and frequencies;
- e. Curve 5: A tube amplifier with low feedback, with harmonics and sub-harmonics of the two test signals standing out.



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You can easily verify this type of distortion generated by the supply based on the experiences with the circuit in *Fig. 1.* It consists of extracting from an amplifier fed by a music signal (by using an isolation capacitor) the AC instability component from the supply, amplifying it, then feeding it into the input of another amplifier to listen



to the spectral composition and amplitude envelope of that component. Subject to a listening test, this signal can take various forms: muted, sharp, or shrill. It can—as the amplifier includes this or that regulator or certain types of circuits—generate distortions emitted like salvos, by bursts during transients, making you think of a tuner being slightly mistuned next to a radio station.

POWER INTERFACE IIM

We all know Matti Otala, a Finnish researcher who discovered the origin of an obscure type of distortion, Interface Intermodulation Distortion (IIM). This new form of distortion, found as a result of a new measurement method, is caused by the amplifier design: the bandwidth of each stage, group propagation time, delay introduced by the various stages with impact on the feedback loop action during transients. Among the different measurement schemes proposed to prove the existence of this type of distortion, there is no lack of interest in those that simulate the appreciable energy caused by the counter-electromotive force of the loudspeaker and the acoustic enclosure, which is re-injected-not as a voltage but as an energy-into the output of the amplifier-while the amplifier itself is reproducing a different frequency.

Actually, the classical distortion

measurements (harmonic distortion, intermodulation distortion according to the SMPTE norms) do not allow detecting it. The basics of this method, which was proposed about 20 years ago by a team of researchers from the University of Musashi, Tokyo, are still relevant today. They are depicted, with some extensions, in *Fig. 2*.

GLASS

The method consists of injecting a 1kHz signal at the input of the amplifier under test to obtain a nominal 15W power into the load at the output. This is either a pure resistive 8Ω load or a loudspeaker. A low output impedance power generator, in turn, through a non-inductive $250\Omega/1000W$ resistor and an LC filter to suppress the 1kHz band (self-induction of 7.5mH/15A plus capacitor 3.3µF), inserts a 50Hz signal into the terminals of the load or the loudspeaker. You thus recover the composite signal present at the load or loudspeaker terminals. This signal is then fed into an audio spectrum analyzer.

As shown in the figure, the composite signal is returned to the amplifier and its input, because it contains a feedback loop. By injecting a second signal into the load, with a frequency much lower than the signal being amplified, the counter-electromotive force is simulated which the loudspeaker would inject into the amplifier.

This secondary signal follows very





PHOTO 4 (top): Amplifier concept 1: An integrated Rotel amplifier, defending the colors of transistor equipment.

PHOTO 5: Amplifier concept 2: A Dynaco amplifier which represents, with flourish, the virtues of tube amplification.

closely in the time domain and the amplitude domain the envelope of the signal being amplified, and is then more or less quickly attenuated and quickly decreases in frequency. These two effects are the result of the electromechanical damping of the moving mass, the air load of the membrane, and the mechanical friction which slow down the movement until the moving parts return to their rest position.

Curve #1 in Fig. 3 shows the original composite signal across the purely resistive load, on the left side the 50Hz signal, and a small residual harmonic (100Hz) from the low-frequency power generator. Curve #2 shows the result from a high-quality amplifier with no IIM distortion phenomena whatsoever. Curve #3, on the other hand, shows an amplifier having excellent harmonic and intermodulation distortion figures (like an average value of 0.008% at half power in the middle of the audio band and slightly more above that) but showing, under these test conditions, large problems of IIM distortion under power.

It is interesting to note, in passing, that this same amplifier, when tested with a slightly larger power output, changes its behavior and produces, as seen in curve #4, an even higher IIM with a completely different shape than in curve #3. The fact that these results vary widely from one amplifier to another makes us wish to know its impact on the sound reproduction quality of each.

It has been effectively shown on the spectrum analyzer that listening to amplifiers with anomalies as bizarre as those seen in curves #3 and 4 have a lack of finesse, bad timbre, or sound inexplicably "hard." However, many tests have shown that amplifiers with relatively high distortion levels because of low feedback factors can present, in this type of power IIM distortion, strong disruptions without being unpleasant to listen to-far from it. That is the case for the model of which the measurement is shown in curve #5, a mono triode amplifier equipped with a 10A/801A triode.

Curve #5 shows elevated distortion

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levels, with a 2nd harmonic at 2kHz and harmonics of the 50Hz signal, all without any other distortions like those in curve #3. Despite these apparent defects, this amplifier reveals itself in listening sessions to be at least as good as the one shown in curve #2. Anyway, you should not lose sight of the fact that you are measuring two conceptually very different pieces of equipment, of different nominal power, for which the other types of distortion hardly have a chance to be the same. Dozens of pages would not be sufficient to examine one by one the different distortion types generated by an amplifier and by the amplifierloudspeaker combination. That is the reason for the importance of critical listening sessions under a strict protocol, despite its limitations and risks of errors, which is seen as the only evaluation method based both on a musical signal as well as simultaneously taking into account a large number of parameters. 1. Reprinted and translated from *Revue du Son & du Home Cinema*, Nov. 2003, "La Distortion dans tous ses états."

2. Translating (or rather transculturizing) this article from French into English, neither of which is my mother tongue, has been an interesting experience. I am indebted to Pascale Genet of the School for French as a Foreign Language in Montpelier, France (www.lefrancparler.fr), for numerous tips and corrections.



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MU: The Last Tube Factory In America

By Eric Barbour

While attending the Winter NAMM show in Anaheim this past January, a fellow named Charles Alexanian appeared at my booth and offered to give me a tour of the MU factory in Oceanside, Calif. Such a rare opportunity can't be passed up, since I already knew that MU was probably the last factory in North America capable of making glass vacuum tubes without depending on numerous outside parts suppliers. The few other firms with equipment for making tubes, such as Richardson Electronics, Groove Tubes, or Western Electric, are either semi-inactive or dependent on outside suppliers for subassemblies.

One evening Charles and I drove down to MU's building in an older industrial area of Oceanside. MU is currently owned by Ronalee Elsberry, daughter of the firm's late founder, Harold Ulmer. She was good enough to show me virtually all of the manufacturing equipment and tooling, and I took as many photos as possible. Charles, who is good friends with



PHOTO 1: Assemblage of all items made at MU Inc. including X-ray tubes.



PHOTO 2: Eisler 8 head sealer (octal size bulbs). Annealing ovens to left of sealer. (*Photos by Eric Barbour; captions supplied by Ronalee Elsberry*).



Roni and also interested in manufacturing power triodes for audio use, has been showing prototypes of his glass directly-heated triodes to possible customers. He also helped me with this brief history.

PAST PRODUCTS

Ulmer originally worked at Hughes Aircraft's old vacuum tube facility (Vacuum Tube Products), which was shut down in the late 1950s. He bought some of the old tooling from VTP and started production of specialized tubes, mostly for military contracts and with the help of some former VTP employees. Much of the green-painted equipment in the photos came from VTP. One of Ulmer's major engineering R & D jobs, after he became independent, was work on the notorious Charactron tube for Convair Aviation. which also made specialized tubes at the time.

The Charactron was one of the most complex CRTs ever made, with an etched metal mask that could be used to shape the electron beam into alphanumeric characters for display along with graphics. Charactrons were used as direction displays in the massive SAGE computer-air defense system. During this time, MU also manufactured Nixie display tubes. Charles tells me that MU still has the special equipment to make Nixies. Ulmer died in September 1997, leaving the business to his daughter, whom he had trained in the complex and obscure business of manufacturing vacuum tubes and who has actively helped manage the company since 1970.

MU made a variety of odd glass tubes over the past 40 years, from the 2C53 high-voltage triode to the tiny vacuum diodes used in Hewlett-Packard 410 series AC voltmeters with built-in RF detectors. Some of the other tubes they made regularly included the 3D21 pulse-power tetrode and its later version 7403, the 6303 radar-clipper diode (a big seller), a version of the 596 rectifier, and several other tubes usually seen only in obscure military equipment such as pulsed radars. MU also made the "e/m" tubes that Cenco Scientific Co. sold to schools for many years, which allowed science students to determine the mass of the electron by direct observation. MU made a ver-



cup for types 6303, 7402. Also used for bulb on EA52 and and 7403 types. EA53 tubes.



PHOTO 3: RF sealing. Used to seal 7056 glass to Kovar PHOTO 5: 12 station exhaust system. Used for 3D21WB



Kovar assembly to bulb for 6303 and 7402 tubes.



PHOTO 4: Litton Mod F-U glass lathe. Used to attach glassed PHOTO 6: Left: used to burn in brands. Right: used for baking bases on tubes. Set up for either 217-C or 2C53 bases.



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sion of the large glass RCA triode type 851, for use in unknown equipment at the Panama Canal.

TUBE DEMANDS

In the 1960s MU manufactured some of the more popular "Bendix Red Bank" tubes, including the 6900 dual triode and 6094 power tetrode. Tooling to make 6900s is still available. According to Charles, if someone "really wanted a tube" to be made at MU, such as an 845 triode, a minimum

production level would be 250 pieces per month. Wholesale price would "be about \$250 each," and the tubes would be "100% handmade." Unlike other defunct tube factories elsewhere in North America, MU still has a skilled labor force available. Manufacturing a 6L6 type would require a minimum of \$100,000 in tooling and development costs, plus several hours of labor apiece. Annual production of 10,000 pieces would lead to a retail price of about \$100. (Please note that these are

GLASS



PHOTO 7: Tung-Sol built age rack. Top ages tube type 122. Bottom ages 3D21WB or 7403.



PHOTO 8: CM furnace (in-house known as dragon furnace). Used for copper brazing X-ray and laser parts. Other brazing bell jars in back for 1 and 2 tip torch brazing.



PHOTO 9: Sylvania automatic grid machine. This one is set up to make grid one of types 7234, 7683, 6842.

very rough estimates.)

As Roni told me, "We can make evervthing in-house except glass bulbs. We can make stems but it is difficult." This is an unusual level of vertical integration for a small tube factory. However, Roni hasn't pursued the manufacture of audio tubes, because of the fickle tastes of the audiophile and guitar-amp market, and their fondness for tubes that might not be perfectly reproducible. Unlike most American businesses, the war in Iraq has been a positive development for MU. They have recently received new orders for their popular types from the US military.

Roni still awaits a serious investor to pursue audio tube manufacture, having received a few recent offers none of which led to any substantial



PHOTO 10: Mid-half of assembly room.

business. The lower costs of Chinese and Russian tubes continue to attract all the major customers. However, as the supply of good NOS audio types dwindles and the demand for better tubes increases, MU could enter this





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PHOTO 11: Automatic cathode spray machine.

production market in the near future. A partner would be required to provide development money and perform marketing to end-consumers.

Eric Barbour is a consulting engineer and is currently owner/designer of

Metasonix. He is also senior editor of Vacuum Tube Valley magazine and has been one of our regular contributors since 1991. He was the winner of the Antique Wireless Association's 1999 Gerald F.J. Tyne Award and 2004 TCA Stokes Award for his efforts in documenting the early history of electronics. Barbour holds a BSEE degree from Northern Arizona University and is a member of IEEE, the Audio Engineering Society, the Antique Wireless Association, and the Tube Collectors' Association.



PHOTO 12: One of the first Charactrons made. Given to MU Inc. after seeing the display tubes.

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