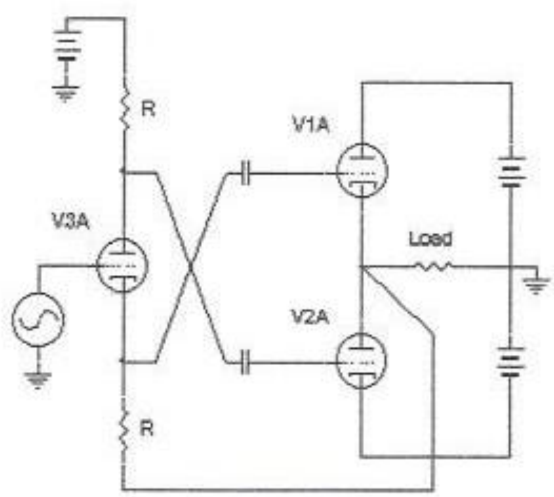
achieve the balanced signals. But even with a high gain tube driving the output stage, the output impedance is relatively high, so the feedback only serves to balance the drives. In this regard, the gain of the driver tube is not fully utilized to achieve full benefits.

If four 6C33C-B tubes were used in the Futterman OTL, biased at 145 V and 400 mA each, the open-loop output impedance would be 25 Ohms (coincidentally, about the same as the Push-Pull Cathode Follower).

The Futterman circuit, and other solutions to driving the SEPP, allow for Class AB operation. Care must be taken if pushing into Class AB2 since the driver circuits are not balanced perfectly, and grid current will introduce assymetry between the top and bottom tubes, and resulting distortion.

A VARIATION ON THE FUTTERMAN

The Futterman is a very clever solution to the problem, but it has the disadvantage of making both tubes behave like common-cathode amplifiers, with their inherent high output impedance. There is a variation of this circuit which appears solves this problem. If the drives to the two tubes are interchanged, the circuit now behaves as a true pair of voltage followers, and the output impedance is dropped down to the theoretical minimum of Rp/(2+2u).



$$Z_o = \frac{R_p}{2(1+\mu)}$$

= 6.8 Ohm with 4 x 6C33C-Bs

Fig. 6: Variation of Futterman OTL

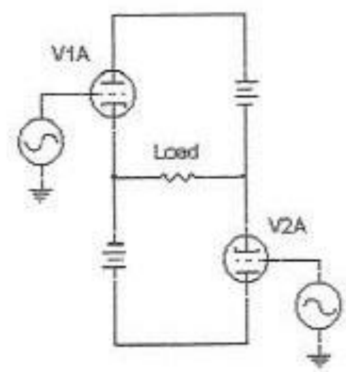
If four 6C33C-B tubes were used in this circuit topology, the open-loop output impedance would be about 6.8 Ohms, **4 times lower than the original Futterman!**

Of course, the lower output impedance does NOT mean that the variation on the Futterman can provide four times as much power. The power handling capabilities of both circuits remain the same, since it is the tube plate characteristics that determine power, as discussed earlier. The circuits will need different drive requirements to get there, but they can both run at the same power level.

Also, this low output impedance could only be achieved with a high gain tube. If pure triode operation were desired for the amplifier, and a realistic gain tube were used, the output impedance would be closer to 3 times lower than the original Futterman circuit.

THE CIRCLOTRON

Instead of concentrating on how best to unbalance the drive signals to compensate for the inherent unbalance in the output stage, a simple modification can be made to the output stage that eliminates the unbalance altogether. If the load and the two power supplies are allowed to float with respect to ground, and if the position of the lower supply and output tube are interchanged, the inherent unbalance of the SEPP is completely eliminated! This arrangement was first used in the Electro-Voice Circlotron of 1955, but was never applied in a commercial OTL until Atma-Sphere Music Systems came out with their MA-1 in the late 1980's.



$$Z_o = \frac{R_p}{2+\mu}$$

= 10.6 Ohm with 4 x 6C33C-Bs

Fig. 7: Circlotron OTL

With the Circlotron arrangement each output tube now behaves in an identical manner. Half the signal across the load appears in the cathode circuit of each tube resulting in partial cathode-follower operation. While the output impedance of this circuit is somewhat higher than the best optimal cathode follower achieved with the Futterman Variation, Rp/(2+u) versus Rp/(2+2u), it is still considerably better than the Rp/2 with identical tubes in a conventional Futterman. Best of all, a conventional push-pull driver stage will give achieve perfect balance with the circlotron, without resorting to circuit tricks, and no feedback around a high-gain tube is used in the driver stage.

If four 6C33C-B tubes were used in the circlotron topology, the open-loop output impedance would be about 10.6 Ohms. Again, not quite as good as what can be achieved with the Variation on the Futterman, but usable.

There are several other advantages to the Circlotron. Both sets of cathodes are at ground potential and can therefore be biased from a common negative voltage. With the SEPP, two bias voltages are required, one ground referenced and the other referenced to the negative rail.

Also, because of the asymmetrical arrangement of the output tubes with respect to the rail voltages, any ripple, power line or signal-induced transient voltages are fed directly into the grid circuit of the lower tubes, via the cathode, where it gets amplified along with the input signal. The upper tubes are immune from this as the rail voltage looks into the plates and therefore does not modulate the grid-to-cathode voltage. The result is a significant hum component at idle and signal-dependent DC offset at higher signal levels. The only way to prevent this from happening is to provide for electronic regulation of both power supply rails, although hum can be reduced significantly with high negative feedback.

With the Circlotron arrangement, ripple and noise on the rail supplies do not affect grid bias. Any modulation of the rails affects only the tubes' plate voltage. Ripple and power line induced transients are automatically canceled in the load, since the load only responds to differential inputs, and these disturbances are common-mode. This is not true for the Futterman circuits.

Given the benefits of the Circlotron: low source impedance, balanced operation and high common-mode rejection, it is possible to dispense with negative feedback altogether. The Atma-Sphere MA-1 is one product that does this. However, despite using 12 6AS7G's in a Circlotron output configuration, however, the damping factor is still too low for good compatibility with many of the lower impedance speakers available. Realizing this, Atma-Sphere offers a tapped auto-transformer to match the 11 ohm output impedance of the MA-1 to a one, two, three or four ohm load.

For many tube users, the concept of adding a transformer to the OTL topology defeats the whole purpose of the exercise - Sorry folks, if it needs a transformer to work properly, it ain't an OTL! It may still sound very good, and the auto-transformer design may be an improvement over other approaches, but it's not the holy grail. (Note: it may also be a lot more reliable than a pure OTL - an important consideration for anyone making these amplifiers for a living.)

CIRCLOTRON WITH FEEDBACK

Perhaps a better way to achieve a low output impedance is to add some overall voltage feedback. Because of the two balanced outputs of the Circlotron, two feedback paths must be used, as in any balanced design.

Since the open-loop output impedance is already low in the circlotron arrangement, not much feedback is needed to get the job done. When operating into a 4 ohm load, only 10 dB of feedback is needed to give an output impedance of less than 1 ohm.

Adding some feedback to the circlotron has the added advantage of correcting for the distortion created in the output stage under large signal excursions. It also permits low-distortion Class AB2 operation of the output tubes. If the driver impedance is kept low and can source sufficient current, it is possible to get almost twice the power that can be achieved with class AB1 operation. But even with low driver impedance, high open-loop distortion is the result when positive grid current begins to flow. If left uncorrected it appears as if the output waveform is clipping. By applying corrective feedback the driving voltage is automatically increased to compensate for this effect, and the full potential of the output tubes can be realized.

CHOICE OF OUTPUT TUBES

The best output tubes for OTL's were all originally developed for service as series pass devices in voltage regulators. These include the 6AS7G, 6080, 6082, 6336/A/B, 7236 and 7241. All these tubes are triodes. This may come as a surprise to some who are only familiar with Futterman-based designs, since these almost exclusively rely on pentodes in the output stage. While Julius Futterman's original OTL design used eight 12B4 miniature triodes, he soon switched to pentodes. This is because with a typical high-impedance ac-coupled driver, incapable of driving the output tube grids positive, the triode cannot generate as much output power as a pentode. But pentodes are inferior in most other respects to triodes. (Anyone interested in an excellent discussion of why triodes are superior to pentodes for OTL service is urged to read Clive P. Locke's "60W OTL/OCL Triode Power Amplifier" in Glass Audio Vol.4 No.4 1992.)

Until recently the best power triode for OTL's was the 6336A. Very popular in Japan and France, it was even mentioned favorably by Futterman in his famous 1954 paper in the JAES. Bothered by the high grid emission of the 6AS7G, as well as by its low mu of 2, he remarks that the then new Chatham 6336, with its higher mu of 2.7, and its 100 ohm plate resistance (with both sections in parallel) performed well in his design.

The 6336A was exceeded only by the Sylvania 7241 triple-triode in low plate resistance. Rated as having a plate resistance of 67 ohms at 550mA, the 7241 never caught on overseas because it was expensive and hard to find. Another tube with limited availability was the EC33C. Made in the Soviet Union especially for the Japanese market (according to Jean Hiraga in "Les amplificateurs O.T.L.") it was presumably a forerunner of the by now famous Sovtek 6C33C-B.

Previously only available for Soviet military use, the 6C33C-B power triode is now readily obtainable in the West, ever since the fall of the Iron Curtain. Very similar in performance to the 6336A but far cheaper, this tube is built like a tank with its thick glass and internal bracing to reduce microphonics. It has quickly become the tube of choice for OTL designers around the world.

THE COVI MARK II CIRCLOTRON OTL

The final topology selected was the circlotron, due to its relatively low output impedance, perfectly balanced operation, circuit simplicity, and low distortion with large-signal and Class AB2 operation. In designing this Covi Mark II circuit, the following modifications were made to the standard circlotron OTL:

- The output tubes were driven with low source impedance, allowing significant positive grid current and high power output into low impedances. Many published circuits, including the Atma-Sphere, have too high drive impedance to operate here. (Probably not a bad idea for reliability reasons!)
- A balanced input phase splitter, implemented with a solid-state current source in the tail of the first tube (yes, solid state is good for some things, and they are inherently good at keeping a constant current).
- Balanced feedback from the output to the input phase splitter was used to produce an output impedance of about 1 ohm with only 10 dB of feedback with a 4 ohm load.
- Separate filament supplies for each half of the output bridge and for the driver tubes.

As used in the Covi Mark II Circlotron OTL, four 6C33C-B tubes generate over 100W into 4 ohms and over 125W into 8 ohms running class AB2 with a plate voltage of 145V. At the sine wave peaks, that's a real 200 W instantaneous, into 4 ohms, which means each 6C33C-B is delivering 3.75 A! Output power can be increased even further (with a corresponding reduction in reliability) with higher plate voltages. For some comments on how reliable this circuit and these tubes are, go to 6C33C-B OTL amplifier reliability.

Further details of this output stage of this amplifier are given on the OTL Amplifier Output Stage Schematic web page.

The input stage is described in detail on the OTL Amplifier Input Phase Splitter Schematic web page.
