

Tube Lovers Anonymous

6C33C-B OTL Amplifier - Background and OTL Circuits

INTRODUCTION

The purpose of this paper is to explain the selection process and trade-offs involved in choosing the circlotron as the optimal topology for a high-power OTL amplifier. The issues involved in making this selection include circuit simplicity, balanced performance under small- and large-signal operation, and achieving low output impedance (and hence a high damping factor) without the excessive use of feedback.

BACKGROUND

For many of us, the vacuum tube remains the only acceptable electronic component for amplifying music. Endless debates and discussions on the merits of solid state versus tubes rage on, but we find that the transparency and realism offered by a device consisting of metal and vacuum just cannot be matched by silicon for sheer musical enjoyment and getting as close as possible to the original sound. Prove what you like, tell us we're imagining things, but we know it just sounds better. However, by insisting on all-tube amplification, there is classically a major penalty to be paid in the power amplifier. Tubes are simply not designed to couple directly to today's modern low impedance speakers, and a transformer must be used to match the power output to the load.

Even with finest modern materials, the output transformer remains the weakest link. At low frequencies its finite inductance steals current away from the load, and at high frequencies its stray capacitance, leakage inductance, and high-frequency copper losses combine to attenuate amplitude and introduce severe phase shifts. From the early days of hi-fi, audio designers strove to create the ideal amplifier. Much effort went into optimizing power transformer design, and even now, the seminal text books on transformers and basic magnetic analysis date back to this early time.

H.S Black discovered negative feedback for electronics in 1934, and it was immediately realized that feedback could go a long way to curing many of the problems introduced by the output transformer and other the electronic amplifying devices. In fact, it was felt that the quality of an amplifier was limited only by the amount of negative feedback that could be applied.

How much feedback that can be realistically applied is limited by how much phase shift exists from input to output of a system. Most of the feedback-limiting phase shift in a vacuum tube amplifier occurs in the output transformer; therefore, if only it could be eliminated, large amounts of negative feedback could be employed, thus creating the perfect amplifier. Today we realize that negative feedback is not the panacea it was once thought to be. In small to moderate doses it can be beneficial, but, as solid-state amplifier designers eventually discovered a generation later, too much feedback always sounds less musical than too little feedback.

As with any problem in engineering, the optimal solution is not to fix it with additional circuitry, but to

remove it altogether. It seems logical then, that if an amplifier can be no better than its output transformer, eliminating the transformer altogether should result in superior performance. Hence the quest for the holy grail of tube amplifier design that has fascinated and tantalized audiophiles for over 40 years: how to design a rugged and powerful Output TransformerLess (OTL) amplifier.

PLATE IMPEDANCE AND EFFICIENCY

The biggest obstacle to building an OTL is the problem of impedance: tubes are designed to be high-voltage, low current devices, and modern speakers need high currents at relatively low voltages. The plate resistance of a tube, typically high, limits the amount of power the tube can supply for a given rail voltage.

Plate impedance alone does not completely determine the available power. It is also affected by whether your choice of circuit forces you into Class A operation (all power tubes always conduct), or whether Class AB (half the tubes may cut off during a half cycle) or Class AB2 (same as AB, but grid is driven positive, resulting in grid current flow) are also possible. However, once the class of operation is determined, available power is determined by plate resistance.

Even using several of the best tubes available, plate resistances are still considerably higher than load resistances. That's OK, you can build an OTL amplifier; it will just be relatively inefficient. For example, a single 20 Ohm plate resistance tube supplying a 4 ohm load can never be better than 16% efficient ($=4/(20+4) \times 100\%$). Reasonable power can still be provided to the 4 ohm load, but it requires a higher supply voltage than the peak output voltage, and you have to accept this and design for the dissipation of the circuit.

PLATE IMPEDANCE AND OUTPUT IMPEDANCE

While we cannot change the inherent plate characteristics of a tube, we can change the way the tube is arranged and driven in an amplifier circuit. This can have a dramatic effect upon the output impedance of the amplifier which tells us how stiff a voltage source we have made. This is also expressed by some as the damping factor of an amplifier - the lower the output impedance, the better voltage source you have achieved. The amplifier will then be better able to handle the nonlinearities, distortions, and back emf produced by the usually very complex speaker load.

The common available topologies for OTL amplifiers have some very important differences in the output impedance characteristics which must be carefully considered when selecting which topology you want to use. Although the power capabilities of the different topologies may remain unchanged when they operate in the same class (A, AB or AB2), the sonics may be substantially different due to the wide range of output impedance that can be achieved.

OUTPUT TUBE PLATE IMPEDANCE

It is important to point out that discussions of plate impedance must be done on small-signal level. In reality, the characteristics of a tube are nonlinear, and the plate impedance, derived at a single operating point from the slope of the I-V characteristics of the tube, will change drastically over a wide range. However, the results of small-signal analysis are still valid - if we come up with a topology that minimizes small-signal output impedance, it will invariably work much better in the large-signal domain also. In other words, it will probably sound better under real conditions.

For the sake of this paper, the 6C33C-B tube will be used for numerical example. At a bias voltage of 145 V, and a plate current of 400 mA, this tube has a plate resistance of 100 ohm, and a gain of 2.7.

At lower currents, the plate resistance increases, a factor to bear in mind when selecting the bias point of the tube. At higher currents, the plate resistance drops - fortunately so, otherwise even the 6C33C-B would be horribly inefficient in supplying a 4 ohm load, and a high-power OTL amplifier would not be practical. At a plate voltage of 70 V, and 1 A current, the resistance of this tube drops to 40 ohm.

This changing plate impedance is another reason to strive to get the output impedance level as low as possible. If the output impedance is high relative to the load, and it changes substantially with current, a significant amount of odd harmonic distortion is created.

THE FIRST COMMERCIAL OTL

The first commercial OTL available was the Stephens OTL which could only power its own specially-designed 500 ohm loudspeaker. It was not a successful product. But this early example demonstrates the primary difficulty of OTL design: how to couple a low- impedance load to a high-impedance vacuum tube without using an impedance-matching transformer. With the introduction of the 6AS7G twin-power triode in 1946, this task started to appear feasible. Its plate resistance is listed at 280 ohms per section; if enough tubes could be combined in parallel, it wouldn't be too difficult to drive a typical loudspeaker load, which at that time was around 16 ohms.

CATHODE FOLLOWER OTL

To get the lowest possible output impedance for a given tube, we must use a cathode follower configuration. This gives an output impedance of $R_p/(1+u)$ where R_p is the intrinsic plate resistance, and u is the gain of the tube. Single-tube cathode follower OTLs can and have been built, although they are very limited in output power, and the problem of dc current in the load must be dealt with.

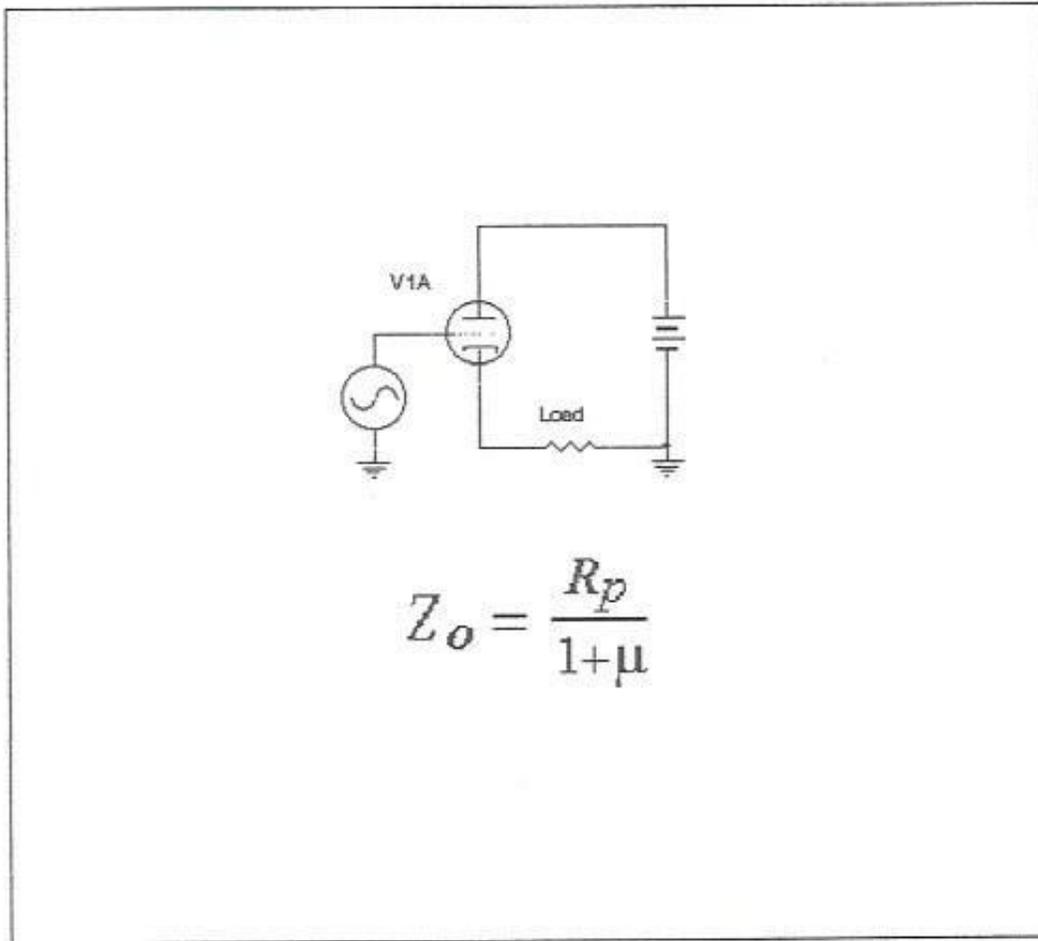


Fig. 1: Cathode Follower OTL

In order to prevent dc current from flowing through the speaker load of this configuration, the speaker can be paralleled with a large inductor which will shunt the dc bias current. This is still an OTL - there is no transformer between the power tube and the load, and none of the detrimental effects of the transfer function from input to output of a transformer coupled load. The most important benefits of OTLs are eliminating the transformer wire, and connecting the speaker directly to the power tube with no other elements in series. However, the low-frequency loading effect of the inductor will detract from the bass performance of this configuration.

This amplifier must, of course, operate in Class A regime only. Since we are concerned here with much higher output power designs, this topology will not be considered further.

COMMON CATHODE OTL

An OTL amplifier can also be connected with the output tube having its cathode grounded. In this common-cathode configuration, the output impedance of the amplifier is much higher, given by R_p , the plate resistance alone. The gain characteristics of this configuration are, of course, different from the cathode follower, and it is preferred by many single-ended purists.

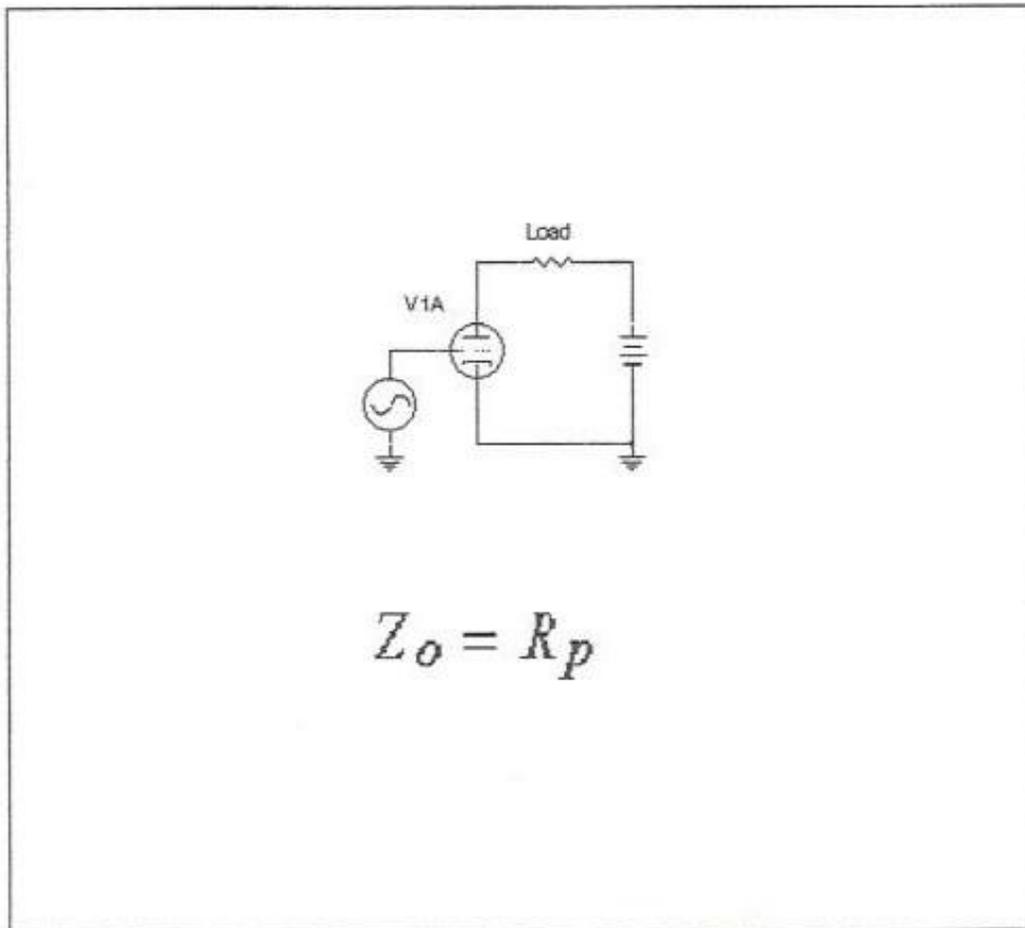


Fig. 2: Common Cathode OTL

As with the cathode follower OTL, the problem of dc current in the load can be mitigated by an inductor in parallel with the load. Also, it must be operated Class A, so it is of little real interest in designing a high power OTL

PUSH-PULL CATHODE FOLLOWER

In 1951 Fletcher and Cooke demonstrated a balanced push-pull cathode follower output stage using eight 6AS7G's that generated 6.32W into 16 ohms. This approach had two distinct disadvantages: its operation was limited to class A, hence the low-power, and its' output impedance was rather high at $2R_p/(1+u)$.

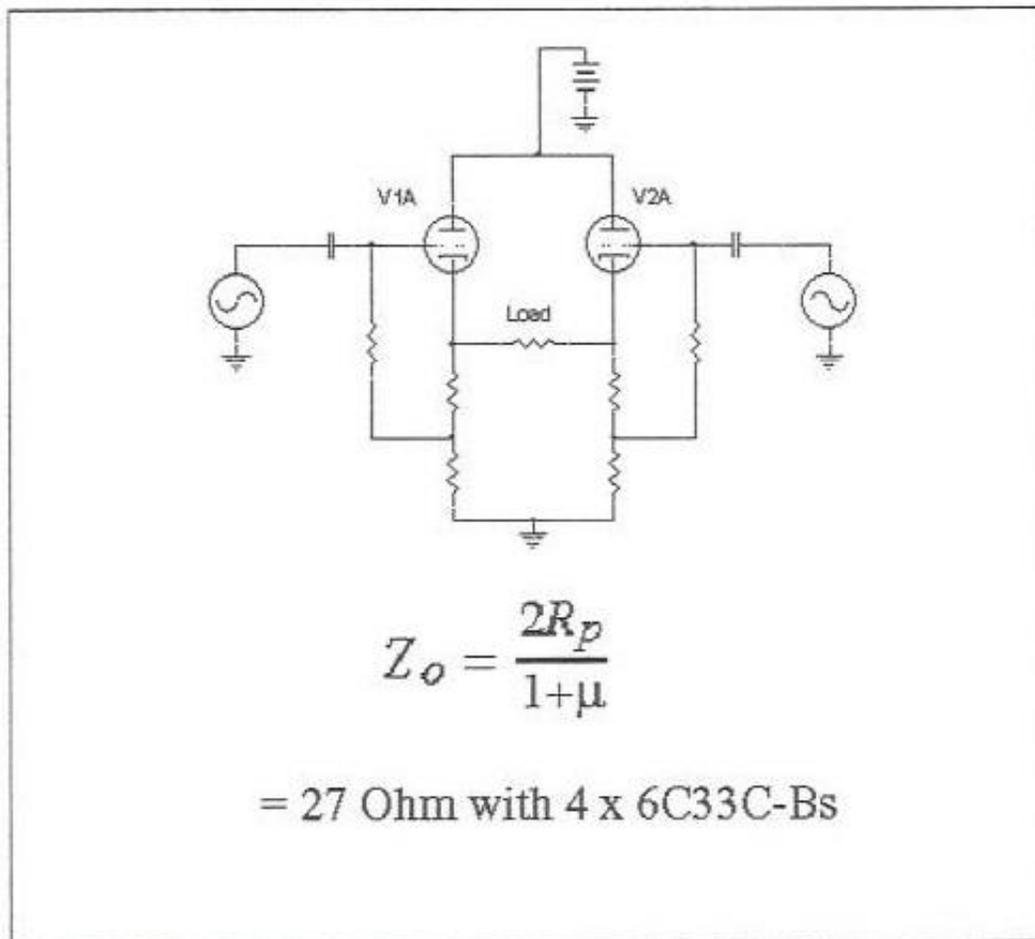


Fig. 3: Push-Pull Cathode Follower OTL

Using two tubes in parallel in the cathode follower configuration of the previous section would give $R_p(2+2\mu)$, the lowest achievable open loop output impedance using a pair of tubes. The push-pull cathode follower output impedance is four times the theoretical minimum because the two cathode followers are in series, not in parallel.

If four 6C33C-B tubes were used in this particular configuration, biased at 145 V and 400 mA each, the open-loop (i.e. before any feedback is considered) output impedance would be 27 Ohms.

THE SINGLE-ENDED PUSH-PULL STAGE

Also in 1951, Peterson and Sinclair proposed what was to become the standard OTL output topology, the Single-Ended Push-Pull, or SEPP. The output circuit is simple, well-suited for class AB or AB2 operation, allowing more output power, but it has one outstanding disadvantage: it is inherently unbalanced.

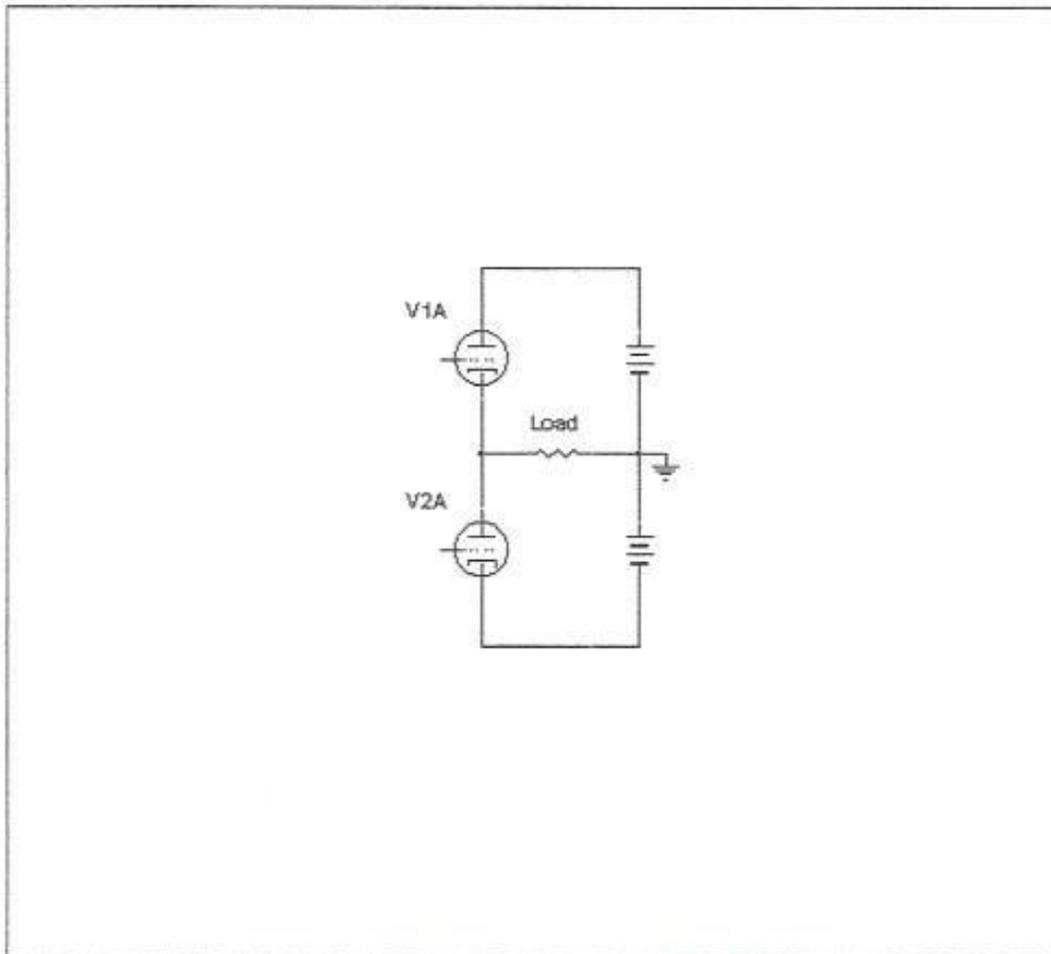


Fig. 4: Single-Ended Push-Pull OTL

In the SEPP output stage the load appears in the cathode circuit of the upper tube and in the plate circuit of the lower tube. If a conventional push-pull ground-referenced driver stage is employed, the upper tubes behave as cathode-followers while the lower tubes act as common-cathode amplifiers.

This creates an imbalance of gain and output impedance between the upper and lower stages, unacceptable in good amplifier design. If true push-pull operation is to be achieved, the upper and lower tubes must be driven with equal but out-of-phase signals, but the presence of the load in the input circuit of the upper tubes makes this difficult to achieve in practice.

In a conventional push-pull amplifier using solid state devices, this problem of balance is overcome by using a P-channel device. Since we only have single-sex electron tubes, and positron tubes do not exist (except theoretically, and perhaps amongst audiophiles of the future on the Starship Enterprise), the SEPP cannot be driven directly, and it must always be considered in conjunction with a suitable drive scheme.

FUTTERMAN'S IDEA

In 1954, a self-taught New Yorker by the name of Julius Futterman published the most famous solution to the problem of a balanced drive for the SEPP. He proposed that the cathode resistor of a split-load phase inverter be returned to ground through the load, rather than to ground, as was the normal practice.

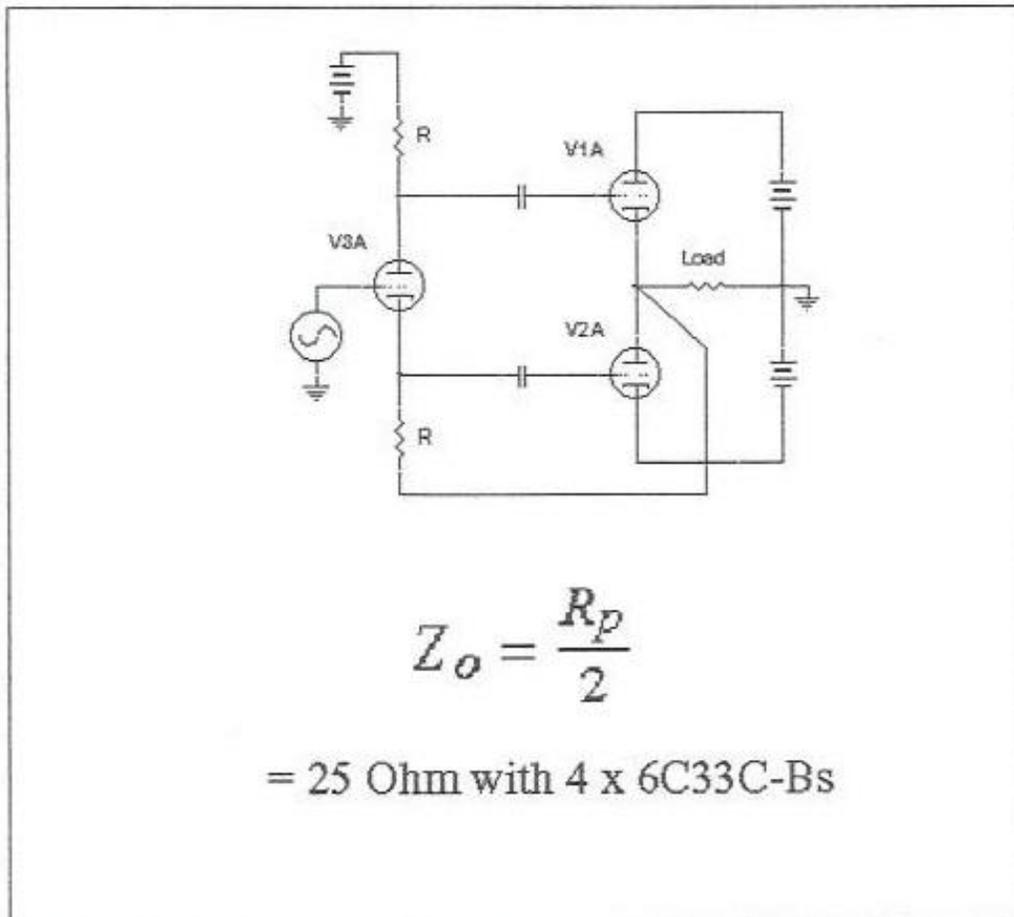


Fig. 5: Futterman OTL

This arrangement results in equal but opposite drive signals being applied between the grid and plate of both sets of tubes. He went on to claim that when so driven, the output tubes are operating as cathode followers. Unfortunately, this is not correct, and Futterman's driver design did not achieve cathode follower operation. This is because the 100% positive feedback introduced by standing the phase splitter on the output voltage effectively canceled the 100% negative feedback from the load that produces the cathode follower effect in the first place.

In other words, Futterman succeeded in converting the upper tube into a common-cathode amplifier, thus matching the behavior of the lower tube, and in so doing lost the cathode-follower impedance advantage! Instead of getting the desired theoretical output impedance of two parallel cathode followers, $R_p/(2+2u)$, the Futterman OTL has the output impedance of two parallel common cathode amplifier tubes, $R_p/2$.

Futterman's solution to provide balanced drives to the SEPP is best known in the US. In Japan, OTL designers mostly used a cathode-coupled phase inverter driver first proposed by Hiroshi Ameniya in 1955. While this driver provided lower drive impedance and twice the signal swing of the split-load phase inverter, it too resulted in the output tubes behaving as common-cathode amplifiers with their attendant high source impedance of $R_p/2$.

It is important to note that the Futterman and other schemes proposed for the SEPP drive use feedback to

