Vacuum Tube Balanced Power Amplifier

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In this article, we will discuss several commonly used vacuum tube power amplifier topologies. Each of them has its merits in audio applications:

a) Single-ended input and single-ended output power amplifier
b) Single-ended input and push-pull output power amplifier
c) Fully balanced power amplifier
d) Output-Transformerless (OTL) power amplifier

As suggested by the name, an OTL power amplifier does not have output transformer. It employs a special circuit to maintain the output at a DC ground level. The discussion of OTL power amplifier is, however, beyond the scope of this article. We will limit ourselves in this article, from a general perspective, to look at vacuum tube power amplifiers (a) to (c) that use output transformer.

Single-ended Input and Single-ended Output Power Amplifier

In the history of vacuum tube power amplifier development, due to its simple design and only few components are required, the single-ended input and output amplifier was first developed. The whole amplifier can use as few as two vacuum tubes. The first tube is a small signal triode that is used to amplify the input signal. The output of the small signal tube is further amplified by a power tube, which also provides the necessary current to drive the load. An output transformer is used to block the direct current while to improve the efficiency in matching the high impedance of the power tube to a low impedance loudspeaker. Both the small signal triode and power triodes are always operated in class-A in this type of amplifier. Since power triodes are highly linear compared with beam power tetrodes and pentodes, even no global feedback is applied the overall distortion of the power amplifier is kept to an acceptable low level for audio application.

The most commonly used power triodes are 2A3 and 300B. They are referred to as receiving type power tubes. A receiving type power triode will deliver from a few watts to about ten watts. Paralleling of two or more power triodes can achieve higher output powers. Another way to get higher power is to use transmitting type power triodes such as 211, 805, 811 and 845. Output power of 20W or higher can be easily obtained with just one such power triode. But a transmitting type power triode requires high power supply voltage at the range of 1000V and generates considerable amount of heat. Safety measures must be in place before putting such power amplifier for domestic use. On the other hand, new and relatively inexpensive power triode 6C33 can deliver almost double of the power from a 300B while the power supply voltage is kept at a reasonable low level.

Figure 1 shows a functional diagram of a single-ended input and output vacuum tube power amplifier. Since the triode in the input and output stages is operated in class-A, the triodes amplify the complete positive and negative cycle of the signals. Due to the class-A operation, the single-ended input and output vacuum tube power amplifier is characterized by the dominated second order harmonic distortion, which renders the sound described as warm and sweet. Unfortunately, class-A amplifier has low efficiency and output power. In addition, DC biasing current of the power triode will always flow through the primary side of the output transformer. In order for the amplifier to have sufficient low frequency response, the iron core of the transformer must be sufficiently large. Thus the result for a high power single-ended input and output power amplifier is inevitably heavy and bulky.

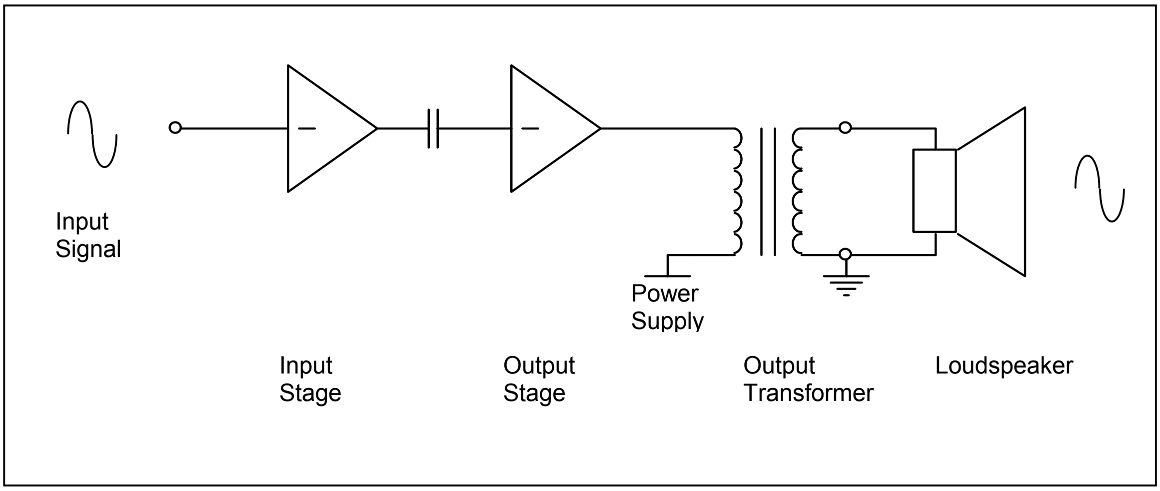

Figure 1. Functional diagram of a class-A single-ended input and single-ended output vacuum tube power amplifier. One of the loudspeaker terminals is tied to the ground.

Single-ended Input and Push-pull Output Power Amplifier

The push-pull output type power amplifier was developed to overcome the shortcomings of the single-ended input and output power amplifiers. Figure 2 shows a functional diagram of a class-AB single-ended input and push-pull output power amplifier. In comparing with Figure 1, Figure 2 has several distinctive features:

- A phase splitter is needed
- Two power tubes are required
- An output transformer that has a center tap is needed so that the two power tubes can operate in the push-pull mode

An ideal phase splitter amplifies the incoming signal and generates two signals that are equal in amplitude but opposite in phase. These two out-of-phase signals are fed to the two output power tubes that are connected to the output transformer in the push-pull configuration. In the push-pull configuration, the positive-phase signal is amplified by one power tube while the other amplifies the negative-phase signal. Since the DC biasing current of the two power tubes are flowing through the output transformer in the opposite direction with respect to the center tap, the output from the transformer is a sum of the different between the signals amplified by the two power tubes. As one of the signal is already inverted (out-of-phase), the sum of the difference will become doubled (i.e., B – (–B) = 2B. B = positive signal amplitude, –B = inverted signal amplitude). Since power is proportional to the square of the amplitude, (i.e., 2B x 2B = $4B^2$), a simple reasoning implies that the push-pull amplifier in Figure 2 may deliver 4 times the power of a single-ended output amplifier of Figure 1. In real practical applications, the push-pull power efficiency will not get four times but it is at least twice of the single-ended output power amplifier. It should be noted that this is not totally unexpected as two power tubes are now used.

What makes a push-pull type power amplifier attractive is that a much smaller size output transformer can be used for the same output power and low frequency response. Since the DC biasing currents of the two power tubes flow oppositely with respect to the center tap of the transformer, the net DC currents flowing through the transformer is zero. Well, at least it is nearly zero if the DC biasing of the power tubes is carefully adjusted. If the net DC current flowing through the output transformer is nearly zero, the iron core of the transformer can be reduced and, hence, a smaller size and lighter power amplifier is achieved.

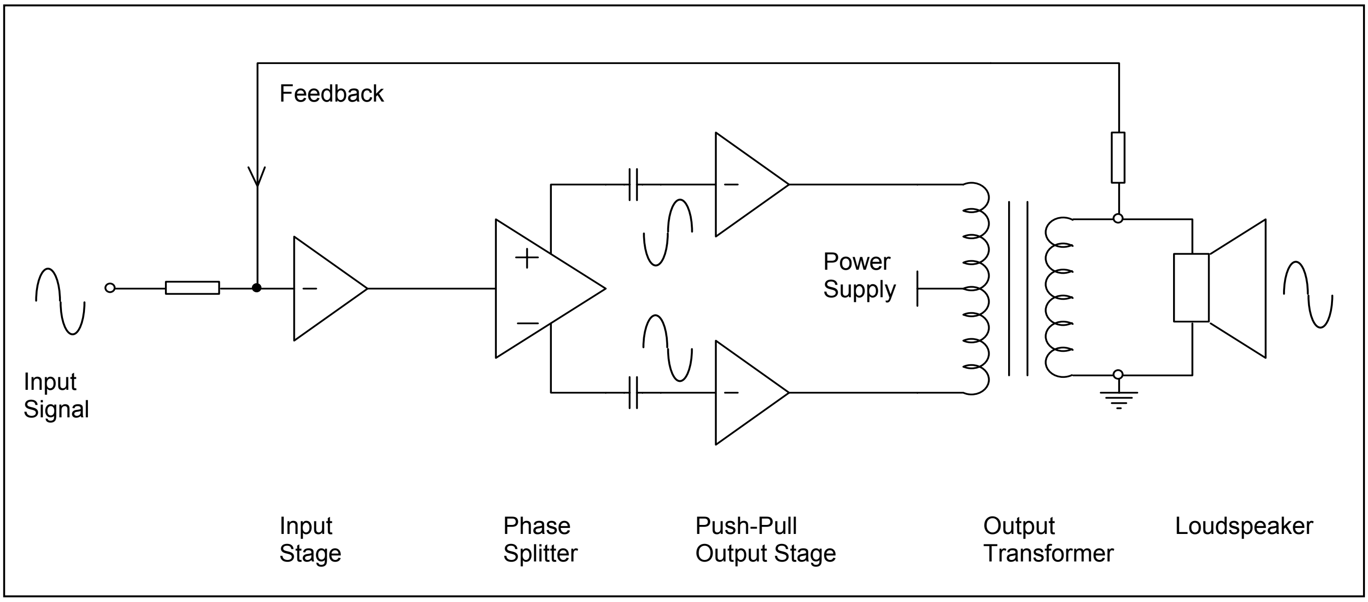

Figure 2. Functional diagram of a class-AB single-ended input and push-pull output vacuum tube power amplifier. A phase splitter is needed to create two out-of-phase signals. One of the loudspeaker terminals is tied to the ground.

To achieve even greater efficiency, beam power tetrodes and pentodes can be used for the power tubes. As the linearity of beam power tubes is not as good as power triodes, a suitable amount of global feedback is usually applied. A push-pull power amplifier generally has lower hum noises as the push-pull operation can cancel them out. And the global feedback will further reduce the overall distortion level. There are a lot of beam power tubes available in the market. Some commonly used beam power tubes include EL84, 6V6, 5881, EL34, 6CA7, 6L6, KT66, KT77, 6550, KT88 and KT90.

In order to obtain the advantages of having low hum noise and distortion, a single-ended input push-pull output type power amplifier needs to have a good phase splitter. There are many classic phase splitters (or called phase inverter) that can be used with good results. They are split-load phase inverter, long-tailed phase splitter and paraphase splitter. Each of them has its merits and shortcomings. The common shortcomings are:

a) Two out-of-phase signals may not have same amplitude
b) Two out-of-phase signals may not be exactly 180 degrees out of phase
c) Two output impedances of the phase splitter may not be the same

The shortcoming (a) is not desirable but, on the other hand, not very critical. As a result of this, the difference of the two push-pull signals will not give the twice of amplitude that it is supposed to.

But the shortcoming (b) is more critical. If the two out-of-phase signals are not truly 180 degrees out of phase, the original signal cannot be truly recovered. In other words, some of the signals are lost or incorrectly re-constructed. The result is a loss of some fine musical details. The shortcoming (c), in some phase splitters, is the cause of (a) and (b).

Fully Balanced Power Amplifier

In order to avoid the above-mentioned shortcomings, it is best to get rid of the phase splitter completely. The function of a phase splitter is to generate two out-of-phase signals. And if the signal source provides the two necessary out-of-phase signals in the first place, a phase splitter is no longer needed. What needed now is just a differential amplifier (long-tailed amplifier) to amplify the two out-of-phase signals. The result is a fully balanced power amplifier as shown in the Figure 3.

The two out-of-phase input signals are given by the output of a balanced line stage preamplifier via a XLR interconnect cable. The first stage of the balanced amplifier of Figure 3 is a differential amplifier that amplifies the incoming signals as well as the feedback signals from the output. The second stage is also a differential amplifier that amplifies and maintains the two incoming signals out of phase. In order to maintain the balanced mode operation, the secondary side of the output transformer has a center tap connecting to the ground.

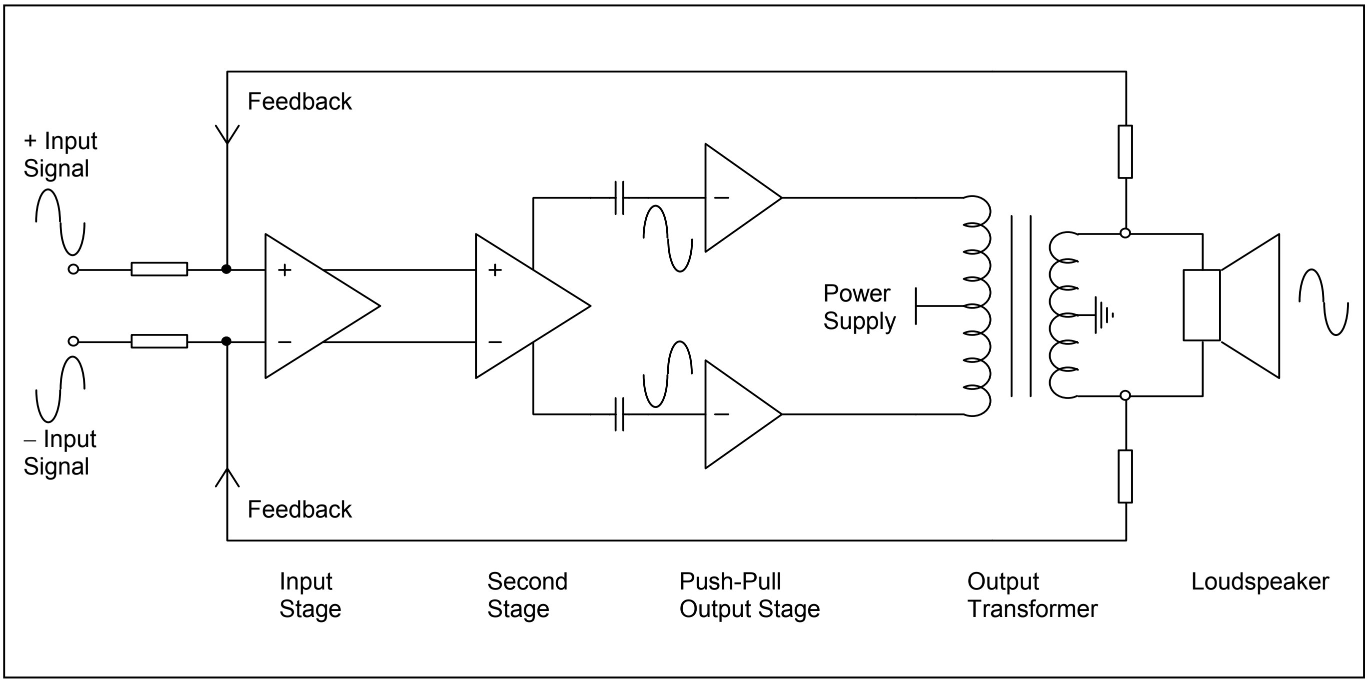

Figure 3. Functional diagram of a class-AB fully balanced vacuum tube power amplifier. No phase splitter is needed. Two out-of-phase signals are given by the input source. No loudspeaker terminal is tied to the ground.

As a matter of fact, it is much easier to build an accurate differential amplifier than to build an accurate phase splitter. Hence, the original signal can be more easily and accurately recovered from the push-pull type balanced power amplifier of the Figure 3 than the single-ended input push-pull output type power amplifier of Figure 2. It is clear from Figure 3 that the balanced power amplifier uses a pair of feedback loops. By applying feedback, we can improve the linearity of the whole amplifier so that the noise and distortion is reduced while the bandwidth is broadened. Although these are all desirable features, applying too much feedback will create instability to the amplifier, whereas applying too little feedback will not obtain the desired results. Thus, it is difficult to optimize the overall performance of a fully balanced power amplifier by using a single pair of feedback.

Figure 4 shows a new balanced power amplifier that employs the patented (US7304535) *Dual Balanced Feedback Topology (DBFT)*. The DBFT allows two pairs of feedback to be used. Therefore, a more flexible way in applying feedback is made possible. The advantages of using two pairs of feedback include:

(a) As the first pair of feedback is connected between the input and second stage, the linearity and bandwidth are increased and the output impedance is reduced for these two stages. These are very desirable features before the signal is amplified by the output push-pull stage.

(b) Each feedback pair only carries a small amount of feedback and hence, the overall stability of the amplifier can be easily controlled. By using two pairs of feedback, the overall performances of the power amplifier can be easily optimized without jeopardizing the amplifier stability.

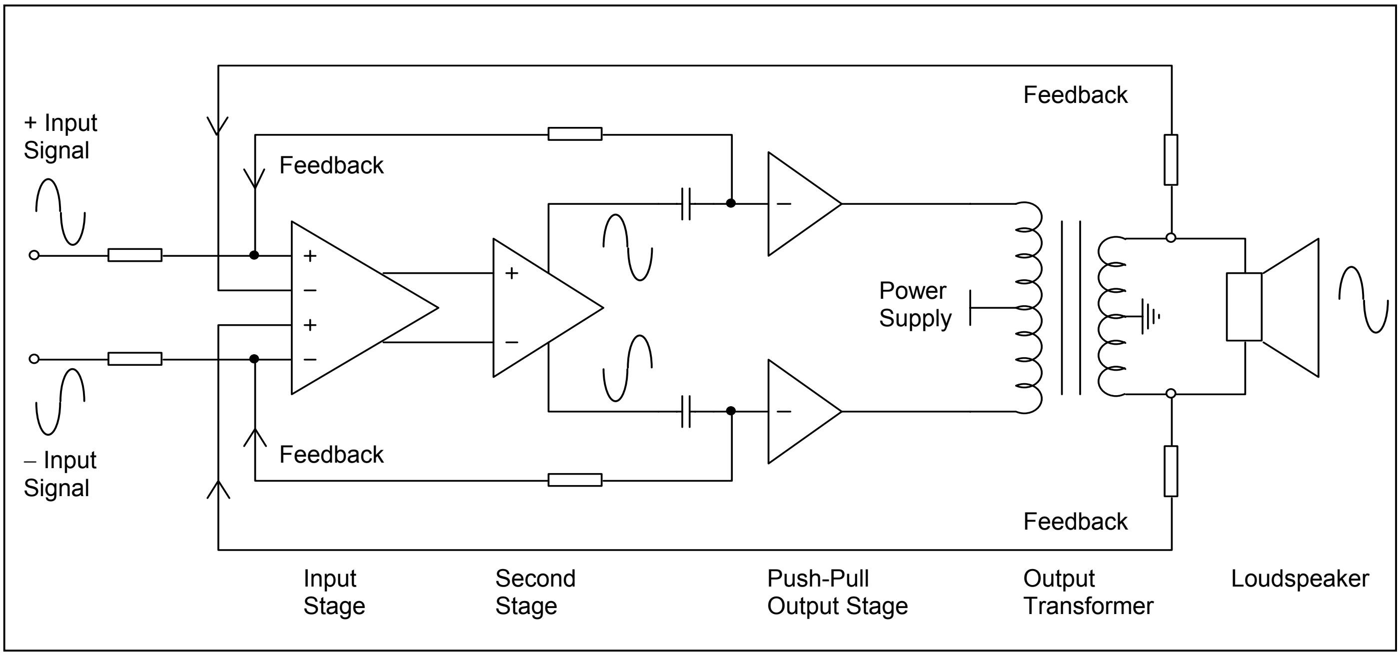

Figure 4. Functional diagram of a class-AB fully balanced vacuum tube power amplifier with patented *Dual Balanced Feedback Topology (DBFT)*. No phase splitter is needed. Two out-of-phase signals are given by the input source. No loudspeaker terminal is tied to the ground.

Conclusion

A balanced amplifier that employs with DBFT, first of all, can completely get rid of a phase splitter that is, however, needed by all conventional push-pull type power amplifiers. Secondly, one pair of feedback is applied to the first and second stages of the power amplifier. Thus the two out-of-phase signals are accurately reproduced so that the fine musical details can be preserved. Thirdly, the second pair of feedback is applied to the overall amplifier. Hence the linearity of the power amplifier is further improved. Finally, due to the balanced operation common mode noises and distortions picked up by interconnect cables can be effectively cancelled out.