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DUAL SINGLE-ENDED AMPLIFIER

BY GRAEME J. COHEN

The operation of a single-output device, in particular the triode valve, has emerged again for serious audiophile listening. The second-harmonic distortion that can be present with single-ended operation is either desired, accepted, or ignored in the quest for high-quality amplifiers. Many engineers disregard valve amplifiers, particularly the single-ended type.

Concept

A new technique uses two single-ended amplifiers per channel, driven correctly and combined in such a way that the total power is added while reducing the harmonic distortion. You drive two identical single-ended output stages with their own output transformers in a differential manner. The combined output power is added, in series or parallel, at the secondaries of the output transformers. You can also use loudspeakers to add the power acoustically.

Each output stage operates in Class A with the normal high-standing current and high flux in each transformer in true single-ended operation. As you increase the flux density in one output transformer, it is reduced in the other, as are also both the second- and third-harmonic distortion products.

Push-Pull

The form of operation with valve output transformer stages is well known (*Fig. 1*). Less known are the several forms of distortion that push-pull operation can produce. High third-order distortion can be present. Symmetrical saturation reduces second-order products but not necessarily third-order. *Figure 2a* shows push-pull saturation.

Any imbalance of the push-pull primary currents can cause high levels of distortion.[1] Typically, 10% imbalance of DC current can cause several percent of harmonic distortion due to the change of flux density (*Fig. 3*).

Large changes of inductance and permeability are present due to the variation of the operating flux from zero to maximum each half cycle (*Fig. 4*).[2–4] Changes of up to 5 to 1 are typical with a flux-density peak followed by a reduction at high levels. This effect is compounded at the speaker resonance frequencies.

Single-Ended

The earliest form of operation is becoming fashionable among audiophiles (*Fig. 5*). The single-ended output stage has some potential benefits. It must be operated in Class A mode, which, unlike Class AB, has minimum distortion at low levels.

The high-standing current requires a large output transformer with an air gap (*Fig. 2b*). This results in low transformer-core distortion and minimum inductance changes with varying flux density. The flux lines are in one direction only, as they do not go to zero over any portion of the Class A operation (*Fig. 6*).

Triode valves are commonly used today in single-ended operation, and due to their low output impedance, there is less transformer distortion. If you operate the triode in a linear manner with low distortion, the transformer distortion dominates, and good design can minimize this.

Dual Single-Ended

When you combine two independent single-ended output stages to give added

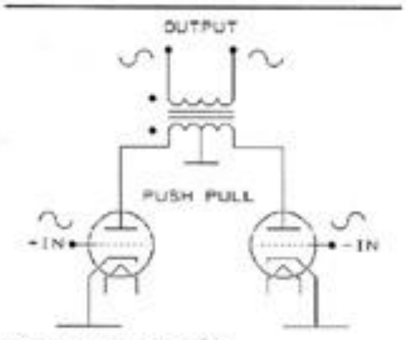

FIGURE 1: Push-pull circuit.

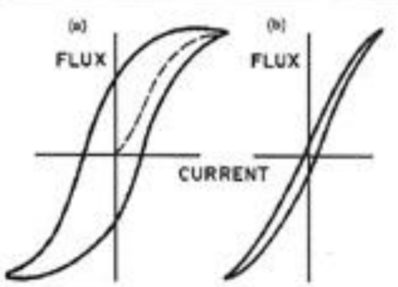

FIGURE 2: Push-pull (a) and single-ended (b) measurements.[1]

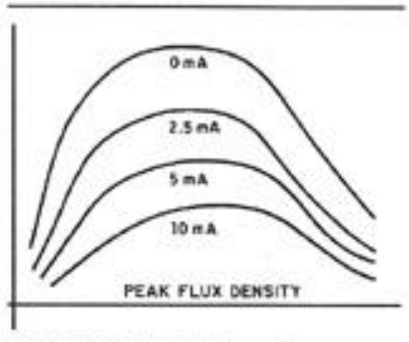

FIGURE 3: Push-pull imbalance.[1]

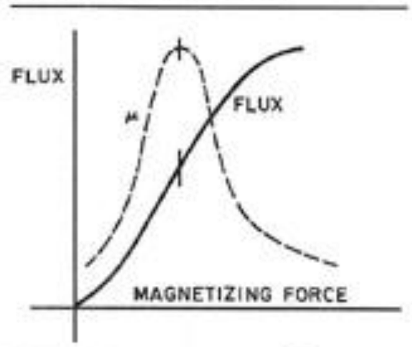

FIGURE 4: Permeability change.[2,3]

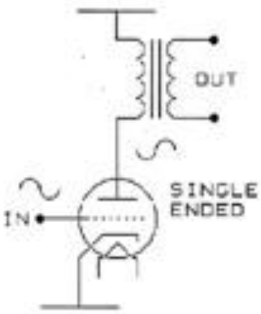

FIGURE 5: Single-ended circuit.

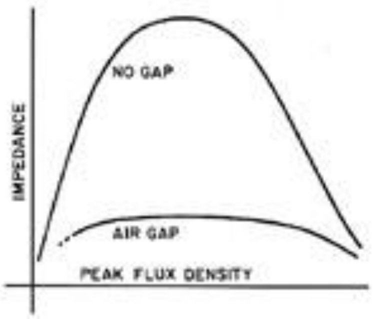

FIGURE 6: Core gap.[1]

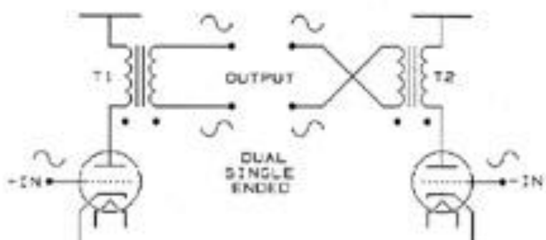

FIGURE 7: Dual single-ended circuit.

power output, but drive them in opposite phase, the overall harmonic distortion is reduced. As one valve and transformer turns on, the other turns off, reducing the distortion products in both the valves and transformers. (*Figs. 7* and *8*). For a nonlinear valve stage, the valve distortion dominates (*Fig. 9*). The valve gain increases at high currents, so the anode-voltage waveform peaks in a negative direction (*Fig. 10*).

If you use a low-distortion valve stage, the transformer distortion dominates due to flux saturation at high levels. At low frequencies, the change in inductance with flux density also modifies the effect of the above conditions.

Output Valves

When a triode valve is in use, the transformer is driven from a low impedance, which produces a-linear voltage across the transformer, with its current having the major distortion component. In the case of a pentode or tetrode valve, the transformer is driven from a high impedance producing a linear current through the transformer, and the major distortion component is the voltage across the transformer.[1]

The screen grid of a pentode or tetrode valve connected as a partial triode (sometimes referred to as ultralinear or distributed loading) is connected to a tap on the transformer primary winding. The relatively high efficiency of these valves is retained, gaining some of the benefits of triode valves. This configuration has a medium output impedance, and the transformer distortion is a combination of voltage and current, which can result in a lower distortion power match to the loudspeaker load.

If you desire a low or zero overall feedback, you need to use triodes to obtain an inherently low output impedance, and hence an adequate damping factor. For zero-feedback operation, you need to use inherently linear output stages with triode valves and wideband low-distortion transformers.[5,6]

Curvature Distortion

With a Class A push-pull amplifier, you may assume that the circuit topology gives the lower distortion. The major benefit of push-pull is to reduce second-order distortion for a given power output per anode dissipation, and compared to a single-ended stage for the same dissipation, this may be the case.

However, due to each half-cycle rounding, Class A push-pull can have considerable third-order distortion (third and fifth harmonic, etc.) because of either the output valve or the transformer. That is, each half cycle may have severe rounding that can cancel for second harmonics, yet have a severe third-harmonic distortion component.

The single-ended topology can have both second- and third-order components. However, when two single-ended output stages are correctly added, each half cycle has cancellation of both second- and third-order components; that is, the rounding of one stage due to an increase of both valve and transformer current tends to be cancelled by the decrease of current in the other stage. As both stages are identical but operating in the opposite phase, it is possible that all forms of distortion diminish during each half cycle, and that the second-harmonic distortion reduction does not depend on the next half cycle. The dual single-ended concept therefore tends to reduce all valve and transformer distortion components during each half cycle.

Figures 11, 12, and *8* show transformer distortion due to flux changes (B) with magnetizing current (H) for

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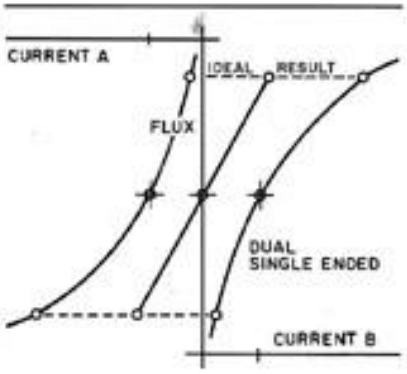

FIGURE 8: Dual single-ended distortion measurements.

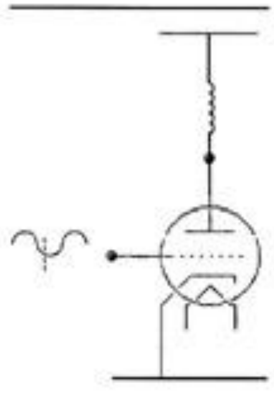

FIGURE 9: Nonlinear valve.

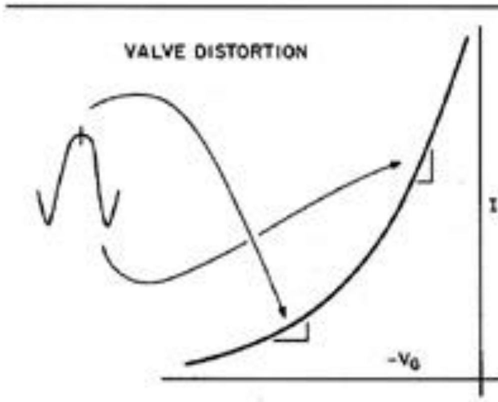

FIGURE 10: Valve distortion.

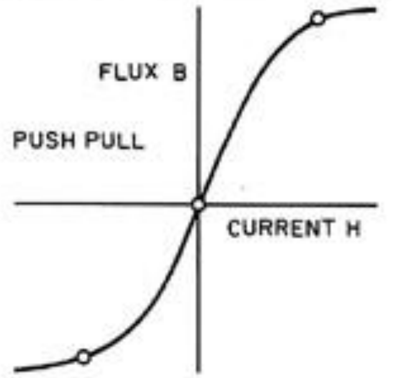

FIGURE 11: Push-pull transformer distortion.

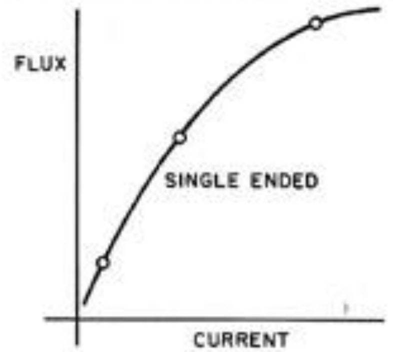

FIGURE 12: Single-ended transformer distortion.

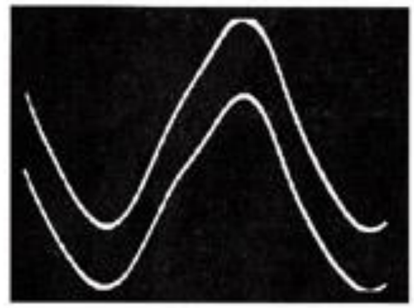

PHOTO 1: Each anode push-pull (one inverted).

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push-pull, single-ended, and dual single-ended, respectively. The push-pull case (*Fig. 11*) shows a high level of third-harmonic distortion (a square wave has low second- but high third-harmonic distortion). The single-ended case (*Fig. 12*) has a considerable level of both second- and third-harmonic distortion, but other attributes, as well. The dual single-ended concept (*Fig. 8*), using two single-ended stages driven out of phase but added to give maximum power output, tends to cancel distortion and thus reduces both second- and third-harmonic distortion. One single-ended stage curve is drawn upside down to show the ideal resultant when combined.

Demonstration

I developed a low-distortion amplifier to show the difference in distortion products between push-pull, single-ended, and dual single-ended output stages. I designed it to have a high output impedance, in contrast to the normal low output, in order to achieve a linear current through the transformer primary winding so that the primary voltage distortion could be readily observed on an oscilloscope. *Figure 13* shows the general form of the test amplifier.

The output valves had high-value cathode resistors with feedback from their cathodes to the input stage. The result was a linear current drive to the output transformer, with no feedback from the transformer itself.

I used a Trimax TA1044 transformer for the push-pull tests and two single-ended Trimax TA851A transformers for the single-ended and dual single-ended tests. I combined the two single-ended transformer secondaries to give maximum output power. The amplifier was driven in a balanced differential manner, with both its halves being independent, identical single-ended designs.

Photos 1–6 show the results for a 20Hz input signal. I took the outputs to an optimum resistive load impedance.

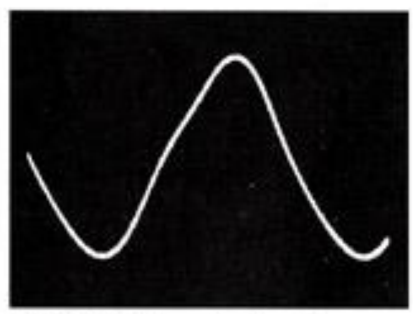

PHOTO 2: Anodes combined in oscilloscope.

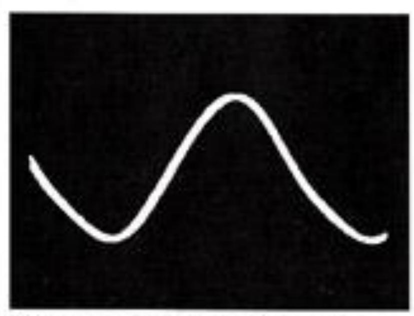

PHOTO 3: Combined secondary waveform.

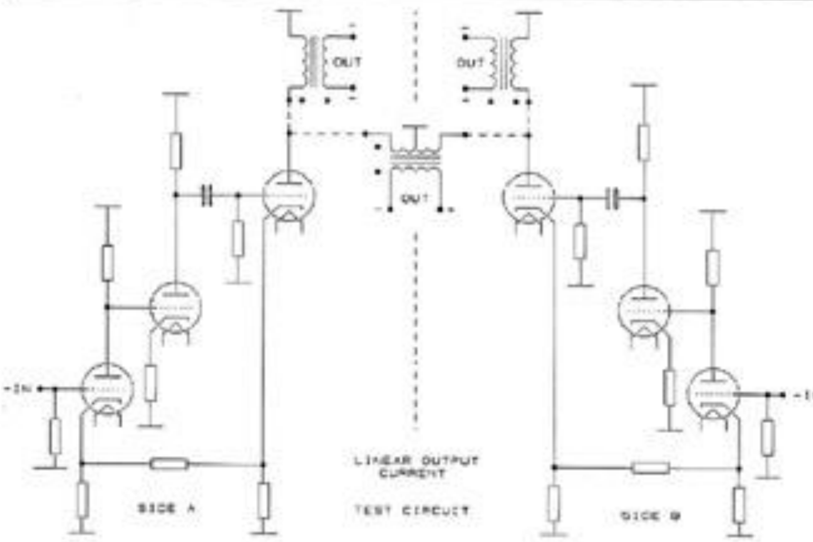

FIGURE 13: Linear output current test circuit.

The total output power was 5W, less than half the transformers' rated power and well inside the linear operation of the current Class A valves. I took the anode-voltage waveforms by inverting one channel of a two-channel oscilloscope.

Photo 1 shows the two anode waveforms of the push-pull transformer connection. The photo is in close agreement with Partridge, parts 3 and 4.[1] *Photo 2* shows the combined anode-voltage waveforms achieved by adding both channels of the oscilloscope. The characteristic kink in the combined waveform is present. The combined output across the resistive load shows the kink just past the midpoint on the waveform (*Photo 3*).

Photo 4 shows the dual single-ended anode waveforms across the two individual single-ended transformers. Again, one oscilloscope channel is inverted. The typical single-ended rounding appears on each waveform. However, when the two anode-voltage waveforms are added in the oscilloscope, the two separate single-ended waveforms combine to show the dual single-ended waveform in *Photo 5*. Note the absence of the kink that was present in the push-pull case. *Photo 6* shows the combined secondary of the two single-ended transformers. Visually, the waveforms appear better than the push-pull case (without the kink). Also, the wave-analyzer measurements show less overall—especially less third-harmonic—distortion.

The above tests may not represent all cases of comparison, but they do show the mechanism for what might be considered high distortion in each single-ended output. In fact, it has less distortion than the similar-power push-pull case, when the two independent single-ended stages are combined in the dual single-ended configuration.

Acoustic Combining

You can combine the two single-ended signals acoustically by driving the dual single-ended amplifier with a balanced differ-

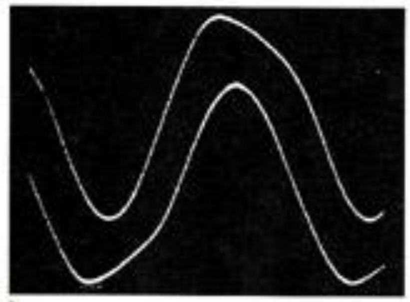

PHOTO 4: Each anode dual single-ended (one inverted).

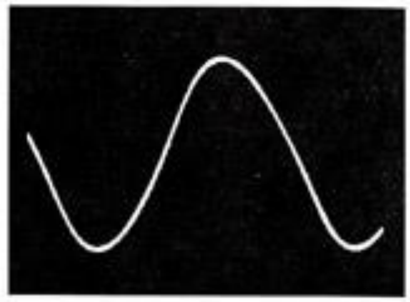

PHOTO 5: Anodes combined in oscilloscope.

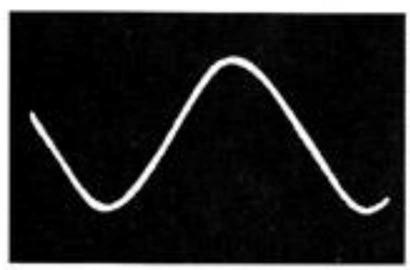

PHOTO 6: Combined secondary waveform.

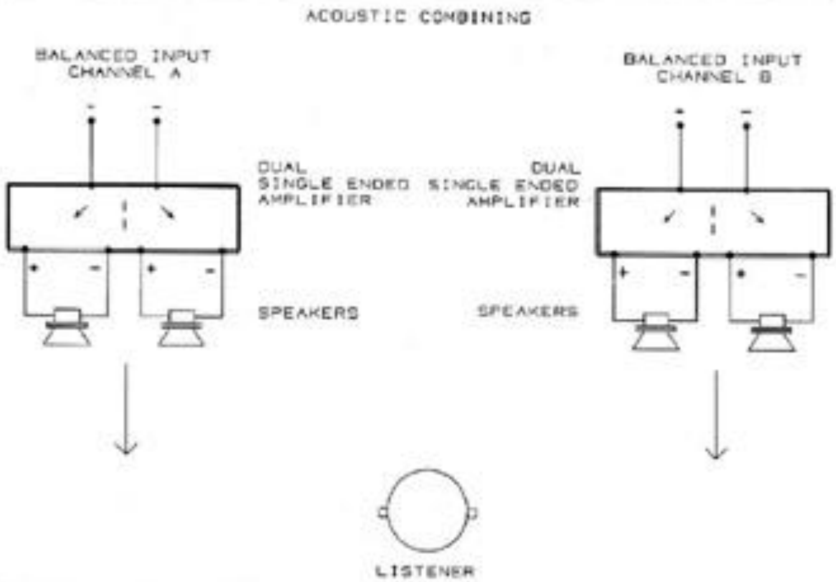

FIGURE 14: Acoustic combining.

ential signal and using two loudspeakers per channel. Just duplicate this arrangement for stereo operation (*Fig. 14*).

In such acoustic combining, a problem may exist with combing effects at high frequencies due to the spacing between speaker driver units. The best option to overcome any combing effects may be a dual single-ended amplifier with correct combining of the two output transformer secondaries driving the usual loudspeaker system. The concept of acoustic combining does have appeal, however, particularly if all loudspeakers are correctly aligned for the stereo sweet spot.

Conclusion

By using two single-ended output stages correctly combined and driven in a balanced differential manner, you obtain the virtues of the Class A single-ended operation with less harmonic distortion. The concept is not limited to valves, since single-ended solid-state amplifiers, suitably combined as described, can achieve similar performance. The dual single-ended amplifier is subject to patent protection. ❖

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