

Figure 18: The spectrum of the class-B complementary-pair FET amplifier without feedback; the two-tone input has 0.06 peak volts in each component. Note that the vertical range here is 100 dB rather than the usual 200 dB.

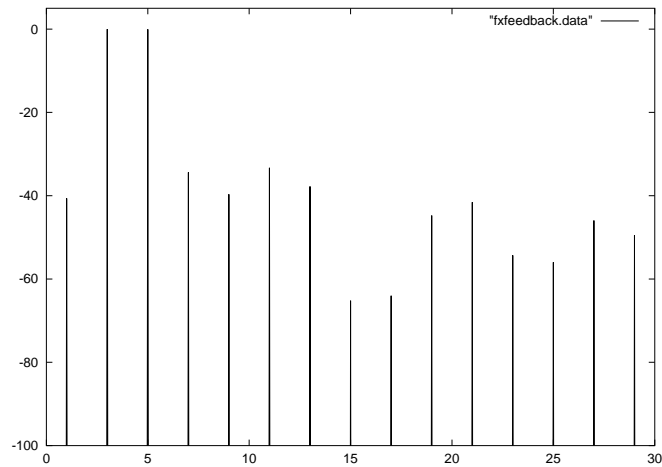


Figure 19: The spectrum of the class-B complementary-pair FET amplifier with 18 dB of feedback; the two-tone input has 0.06 peak volts in each component. Note that the vertical range here is 100 dB rather than the usual 200 dB.

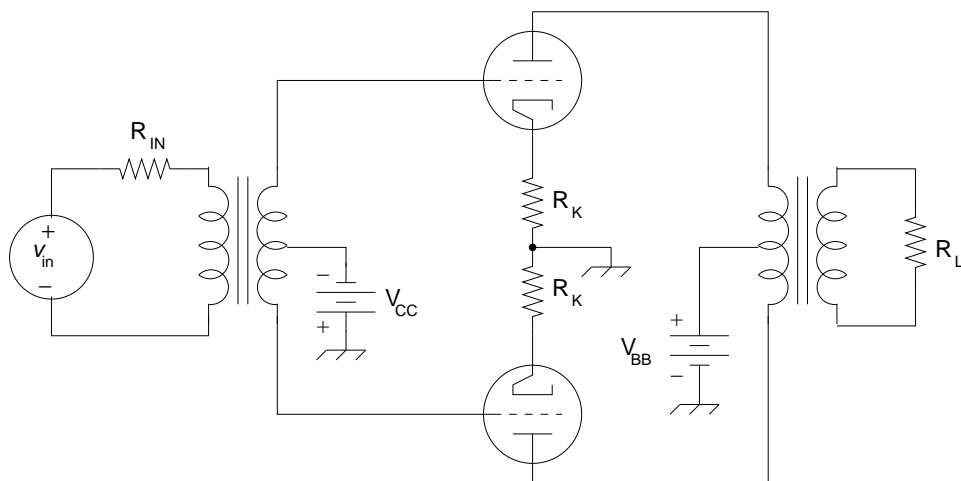


Figure 20: An idealized push-pull stage constructed from vacuum triodes.

We can maintain an overall gain of 10 while introducing 18 dB of feedback by increasing the prescalar gain to 100.

The spectra are interesting. Figure 18 shows the spectrum of the amplifier without feedback; figure 19, that of the amplifier with feedback. While feedback generally improves the signal, the distortion is still pretty bad; and the products at frequencies 23 and 25 are much worse with feedback than without feedback. Indeed, the component at frequency 25 is almost 20 dB worse with feedback!

This effect disappears with larger excitation signals, where the crossover region is a smaller portion of the waveform. As the size of the excitation increases the distortion generally decreases and the feedback becomes uniformly effective. For smaller excitations the relative distortions worsen both with and without feedback.

## Vacuum triode push-pull output stage

Because vacuum triodes do not come in complementary pairs a push-pull amplifier built from triodes is configured somewhat differently from one built with semiconductor devices. The traditional method is to use center-tapped transformers to provide a phase inversion at input and the output. Unfortunately, transformers that provide good performance over a wide range of

frequencies and amplitudes are expensive and hard to manufacture, especially if they must be used with significant bias current; thus most modern audio amplifiers do not use transformers. In the simple circuit of figure 20 we assume nonetheless that the 1–1 transformers are ideal, and that the tubes are identical.

In this circuit, which we analyze only in class A, we can adjust the amount of cathode degeneration, plate current and voltage gain by adjusting  $R_K$ ,  $V_{CC}$  and  $R_L$  respectively. (In a real circuit,  $R_L$  would be given, and we would change the output transformer turns ratio to adjust the effective load resistance.) We set the voltage gain to 10; plate bias current, to 10 mA; and peak voltage in each input component to 0.1 volts. This is higher than we used in the other circuits, because the distortion of the triode circuit turned out to be very low.

In figure 21, we see that, allowing for the level difference in the input signal, the low-order part of the spectrum of the push-pull amplifier without feedback is very similar to the spectrum of the single-ended tube amplifier (figure 12) with the even-order components suppressed. However, there are some new high-order components (with frequency larger than 15). The spectrum with  $R_K = 100 \Omega$ , a moderate amount of feedback, proved much better (figure 22).

In the class-A vacuum triode push-pull stage the relative distortion decreases with decreasing signal amplitude, with or without feedback. This is in stark contrast to the behavior we observe with the class-B FET complementary-pair stage. In that case the relative distortion increases as the signal amplitude decreases. This is because the size of the nasty region near zero is constant in the class-B stage. (On the other hand, the class-A FET pair had zero distortion!)

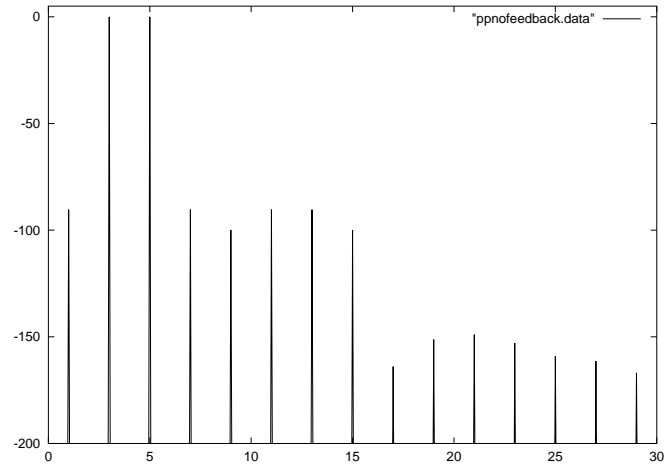


Figure 21: The spectrum of the push-pull vacuum triode amplifier without feedback; the two-tone input has 0.1 peak volts in each component.

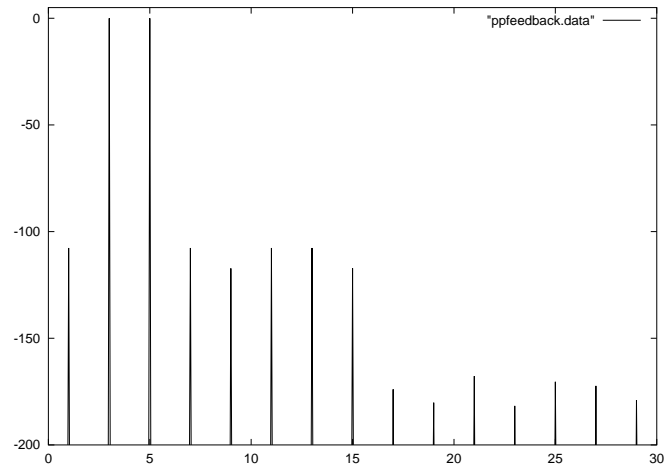


Figure 22: The spectrum of the push-pull vacuum triode amplifier with feedback; the two-tone input has 0.1 peak volts in each component.

## Summary of output amplifiers

For all cases, input signals were at frequencies 3 and 5 (unscaled). Input voltage levels were always equal for the two components and were as given below. Unless otherwise stated, (a) Higher input level raises the relative distortion and (b) emphasizes higher-order distortion products. (c) Adding more feedback lowers all distortion products.

1. BJT: 0.005 peak volts in each input component

Complementary pair analyzed in class A only. Distortion products of even-numbered frequencies are absent due to circuit symmetry. However, the pair without feedback, compared to the single-ended BJT stage without feedback, generates frequencies 17, 25, 27 and 29 at levels much higher than expected. And the pair with feedback, compared to the single-ended BJT with feedback, generates 17, 19, 21, 23 and 25 at much higher levels than expected.

2. FET: 0.06 peak volts in each input component

Symmetrical source follower, with N-type pullup analyzed in class A and class B. In class A, the pair is distortion-free even without feedback, and feedback's only role is to set gain. In class B, even-numbered distortion products are absent due to circuit symmetry; but frequencies 23 and 25 get worse with feedback! Also in class B with or without feedback, relative distortion goes up as input level goes down.

3. Triode: 0.1 peak volts in each input component

Push-pull circuit analyzed in class A only. Even-numbered distortion products are absent due to circuit symmetry. Feedback suppresses all products.

## Differential input stages

The long-tailed differential pair appears as the input stage in many audio amplifiers. It can be used to provide common-mode rejection on a balanced input, or a convenient place to apply global DC feedback, allowing the designer to control the bias as well as the gain with the feedback network. This remarkable circuit can be realized with a matched pair of tubes, BJTs, or FETs, as in figure 23. If a single-ended output is needed then only one output need be used, at the cost of a factor of two in gain (though if current mirrors are available in the technology we can get a single-ended output without loss of gain).

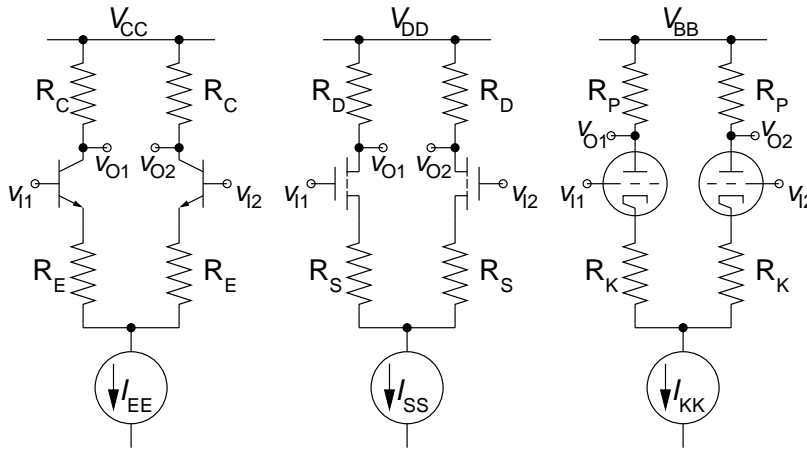


Figure 23: Differential pairs can be constructed using any transconductance device.

In the ideal case we drive the differential pair with a current source and the current is divided between the two branches. If the input voltages  $v_{I1}$  and  $v_{I2}$  are equal then the current is divided equally and the voltage drops across the load resistors are equal, so the output voltages  $v_{O1}$  and  $v_{O2}$  are equal. If the input voltages differ then more of the current is routed through the branch with the higher input voltage and thus that branch has a lower output voltage than the other one. If the differential input voltage  $v_{I1} - v_{I2}$  is too large then all of the current is routed through one branch, pinning the pair. If the current source is perfect then the differential pair is insensitive to common-mode variations in the input voltages.

In the circuits of figure 23 we have included degeneration resistors (emitter, source, cathode) to allow us to introduce feedback. In a differential pair such degeneration can help us to compensate for the fact that the devices are not perfectly matched, and it allows us to exchange gain for an increase in the range of differential input voltages for which the pair has approximately linear operation.

The analysis of a differential pair with degeneration resistors is rather involved, requiring us to work with a nasty set of nonlinear equations, which must be solved numerically. Here we show the equations for the case of the vacuum triode pair; the other cases are similar, but a bit easier.

The plate currents in the triodes are

$$i_{P1} = K(v_{PK1} + \mu v_{GK1})^{3/2} \quad (51)$$

$$i_{P2} = K(v_{PK2} + \mu v_{GK2})^{3/2}, \quad (52)$$

where

$$v_{PK1} = (V_{BB} - R_P i_{P1}) - (v_{I1} - v_{GK1}) \quad (53)$$

$$v_{PK2} = (V_{BB} - R_P i_{P2}) - (v_{I2} - v_{GK2}). \quad (54)$$

The branches are connected by two facts: the plate currents must sum up to the current source

$$I_{KK} = i_{P1} + i_{P2}, \quad (55)$$

and Kirchoff's voltage law must hold

$$v_{I1} - v_{GK1} - R_K i_{P1} + R_K i_{P2} + v_{GK2} - v_{I2} = 0. \quad (56)$$

Finally, if we know the plate currents, we know the output voltages:

$$v_{O1} = V_{BB} - R_P i_{P1} \quad (57)$$

$$v_{O2} = V_{BB} - R_P i_{P2}. \quad (58)$$

We simulated differential pairs built with BJTs FETs and triodes, with and without feedback. The results are what we would expect. The spectra show only odd-order terms: the even-order distortions are cancelled by the symmetry of the system. By choosing the scale of the input signals and the amount of feedback, we could get the main distortion products to be approximately the same size for each circuit both with and without feedback.

For the BJT differential pair we set the current source at 1 mA, so the bias current for each BJT is 0.5 mA. This gives us a transconductance of about 19.3 mS. With no feedback (emitter resistors omitted) we obtain a gain of 10 with collector resistors of about 520  $\Omega$ . To add feedback we install the emitter resistors. With emitter resistors of 217  $\Omega$  we had to increase the collector resistors to 2700  $\Omega$  to maintain the amplifier gain of 10.

In the BJT spectra (figures 24 and 25) the strongest distortion terms are the third-order intermodulation products at frequencies 1, 7, 11, 13, followed by the third harmonics at frequencies 9 and 15. Without feedback the intermodulation is at about -53 dB and the third harmonics are at about -62 dB. With feedback these components are suppressed to -96 dB and -105 dB respectively. However, to keep the distortion this small the BJT differential pair must be operated with very small input signals. Here we use 5 mV peak in each component.

For the FET differential pair, we set the current source at 2 mA, so the bias current for each FET was 1 mA, giving a transconductance of 2 mS. With no feedback (source resistors omitted) we obtain a gain of 10 with drain resistors of 5000  $\Omega$ . We set the current source for the triode pair at 10 mA, so the bias current for each triode was 5 mA. (The transconductance was not computer here, because for triodes the plate current depends also on plate-cathode voltage.) With no feedback (cathode resistors omitted) we obtain a gain of 10 with plate resistors of 1530  $\Omega$ .

We adjusted the input signal levels for the FET and triode pairs so that, without feedback, the strengths of the strongest distortion products would be about the same as that of the corresponding lines in the BJT spectrum without feedback. Where the BJTs were running at 0.005 peak volts in each input component, the FETs could handle 0.15 peak volts and the triodes 0.35 peak volts (a mighty big input signal!)

Then we adjusted the amount of feedback in the FET and triode circuits so that, again, the distortion products would come as close in level as possible to those of the BJT with feedback. For the FETs, this was accomplished with source resistors of 2000  $\Omega$ ; and the drain resistors were then chosen to be 25,000  $\Omega$  to give the desired gain of 10. For the triodes, this required cathode and plate resistors of 400  $\Omega$  and 7500  $\Omega$ , respectively.

The spectra for all three devices are remarkably similar, reflecting the good behavior of differential-pair topology with all three types of devices. The FET pair (figures 24 and 25) show minor differences from the BJTs in the second tier. The triodes produced a second tier with higher levels than



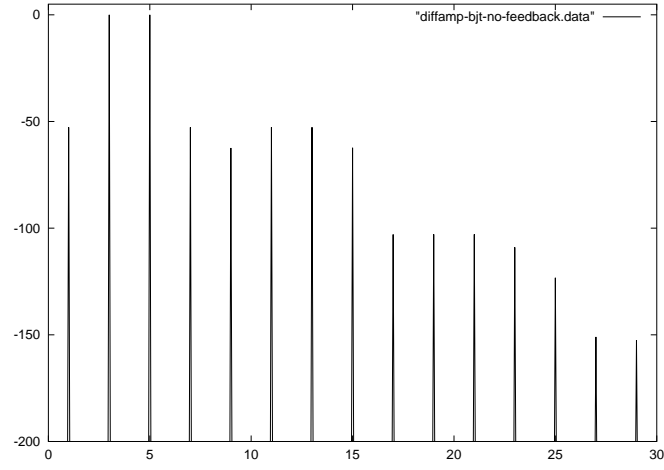


Figure 24: The spectrum of the BJT differential pair without feedback; the two-tone input has 0.005 peak volts in each component.

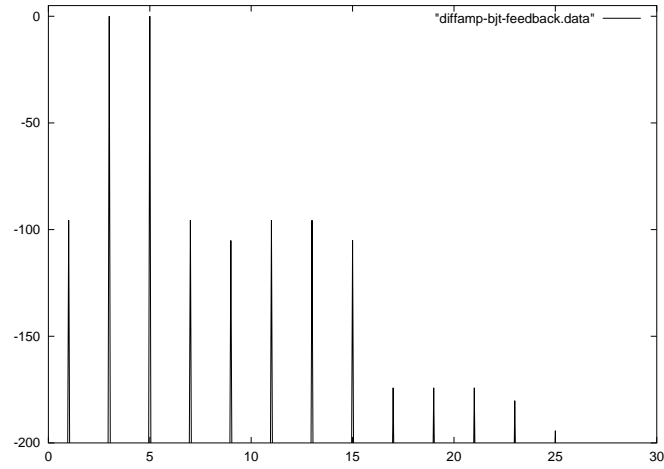


Figure 25: The spectrum of the BJT differential pair with feedback; the two-tone input has 0.005 peak volts in each component.

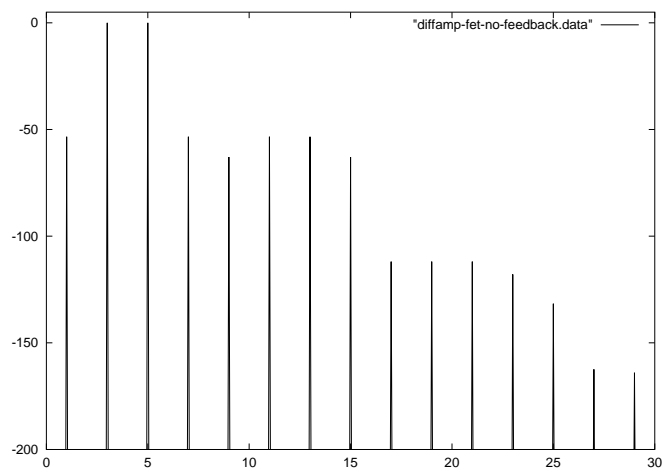


Figure 26: The spectrum of the FET differential pair without feedback; the two-tone input has 0.15 peak volts in each component.

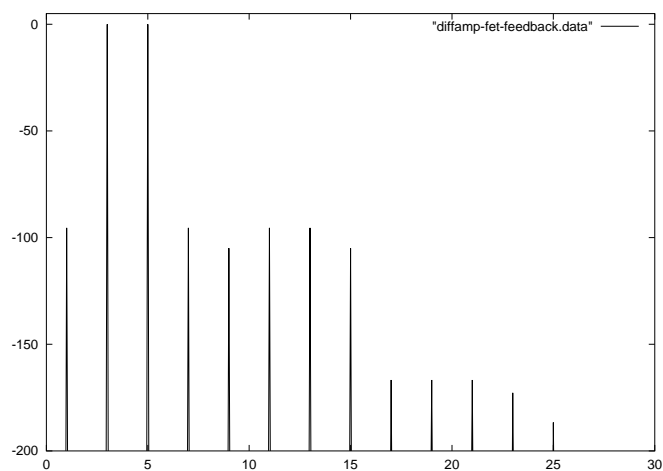


Figure 27: The spectrum of the FET differential pair with feedback; the two-tone input has 0.15 peak volts in each component.

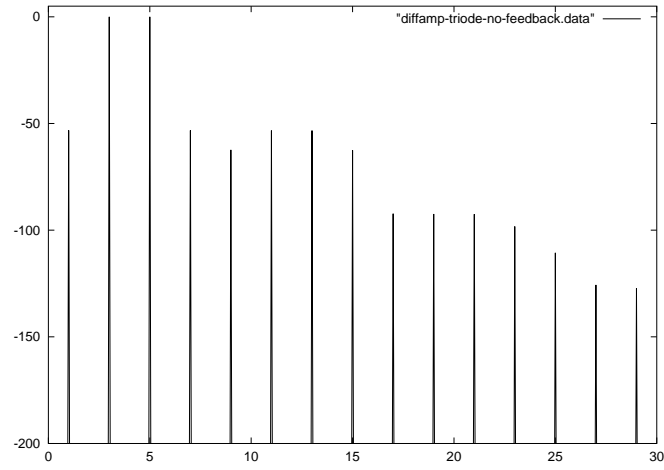


Figure 28: The spectrum of the triode differential pair without feedback; the two-tone input has 0.35 peak volts in each component.

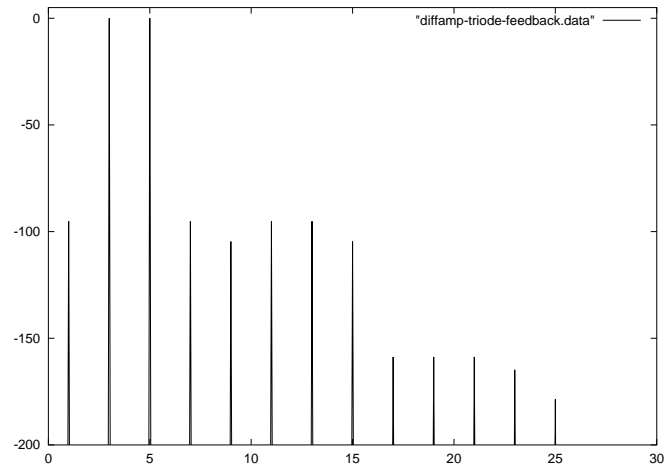


Figure 29: The spectrum of the triode differential pair with feedback; the two-tone input has 0.35 peak volts in each component.

the BJT or FETs, but with feedback they were all down more than 150 dB.

Further experiments indicate that the distortion only decreases with decreasing signal strength, and that feedback only helps.

## Summary of differential-input amplifiers

For all cases, input signals were at frequencies 3 and 5 (unscaled). Input voltage levels were always equal for the two components and were as given below. Unless otherwise stated, (a) Higher input level raises the relative distortion and (b) emphasizes higher-order distortion products. (c) Adding more feedback lowers all distortion products.

1. BJT: 0.005 peak volts in each input component
2. FET: 0.15 peak volts in each input component
3. Triode: 0.35 peak volts in each input component

## Discussion

In all cases, with and without feedback, intermodulation terms dominate the harmonic distortion terms of the same order. We all know this must be true, but we usually forget it.

Feedback generally improves the intermodulation behavior of the amplifier fragments we have examined, but the exceptions are interesting: the performance of a single-ended FET stage can be made significantly messier with feedback; and strange things happen when we apply feedback to a FET class-B complementary pair.

The tube amplifier fragments start off nicer than BJTs and FETs—and they keep the advantage of handling bigger signals for a given amount of distortion—but BJTs can be made very nice with lots of feedback. And a class-A FET complementary pair is distortionless, if you can find perfectly-matched FETs that perfectly follow the theoretical square law. Unfortunately, it is hard to find well-matched FETs, and the FET model that this conclusion is based on is rather crude. We do not know what happens with a more accurate model of any particular FET pair.

The spurious signals generated by feedback in the single-ended FET amplifier, and enhanced by feedback in the class-B FET pair, are correlated

with the program material, since they are constructed from sums and differences of integer multiples of the program-material frequencies. We do not know whether or not this program-correlated noise is psychoacoustically significant, but its presence is certainly suggestive.

So high-order products can be enhanced by feedback in some simple amplifier stages. Although we have not investigated whether or not this happens in more complex amplifiers, it is tempting to relate this finding to the perception of feedback introducing what can sound like a badly-integrated “super-tweeter”. Similarly, the fact that feedback can sometimes increase the relative distortion of very low-level signals makes it tempting to relate this finding to the loss of fine detail and room sounds. Whether or not these are appropriate attributions can be determined only by psychoacoustic experiments.

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# Bibliography

- [1] Amperex specifications for tube type 6DJ8/ECC88, September 1960.
- [2] James Boyk. “There’s Life Above 20 Kilohertz! A Survey of Musical Instrument Spectra to 102.4 kHz,”  
<http://www.cco.caltech.edu/~boyk/spectra/spectra.htm>.
- [3] Daniel H. Cheever, *A New Methodology for Audio Frequency Power Amplifier Testing Based on Psychoacoustic Data that Better Correlates with Sound Quality*, S.M. Thesis, University of New Hampshire, December 2001.
- [4] Norman Crowhurst, “Some Defects in Amplifier Performance Not Covered by Standard Specifications,” in *Journal of the Audio Engineering Society*, October 1957, pp. 195–201.
- [5] S. Holmes, G. J. Sussman, J. Boyk, *On the Characteristic Spectra of 28 Varieties of Feedback*, Cambridge: Beekeepers Press, 1899.
- [6] W. Marshall Leach Jr, “Spice Models for Vacuum Tubes Amplifiers,” in *Journal of the Audio Engineering Society*, March 1995, p. 117.
- [7] Matti Ojala, “Transient distortion in transistorised audio power amplifiers,” in *IEEE Trans. AU-18*, **3**, 1970.
- [8] T. Roddam, “Calculating transient response,” in *Wireless World*, **58**, 8, August 1952, p. 292.
- [9] D.E.L. Shorter, “The influence of High-Order Products in Non-Linear Distortion,” in *Electrical Engineering*, April 1950, pp. 152–153.