

THE AMPLIFIED NEGATIVE FEEDBACK CURRENT SOURCE AND VOLTAGE SOURCE

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Introduction

The amplified negative feedback (ANF) current source is a workhorse of discrete audio frequency amplifier design. This delightfully elegant little circuit can even be modified to function as a low impedance voltage source—the ANF voltage source—with the inclusion of a diode or two, an LED or a zener diode, as shall be demonstrated.

The ANF Current Source

The ANF current source (**fig. 1**) possesses two negative feedback loops: a major negative feedback loop and a minor negative feedback loop. The latter is series derived, series applied negative feedback local to the current source transistor **Q1**, courtesy of its emitter resistor **R1**, while the major negative feedback loop is series derived, shunt applied, with the feedback voltage appearing across resistor **R1** amplified by control transistor **Q2** and then applied, courtesy of transistor **Q2**'s collector, to the base of current source transistor **Q1**. As far as the major loop transmission path is concerned, the current source transistor **Q1** operates as an emitter follower, while the control transistor **Q2** operates as a common emitter stage. Biasing resistor **R2** acts as the collector load of control transistor **Q2**.

The output impedance of a nominal current source may be simulated in SPICE by connecting the output of an ideal grounded independent voltage source to the output of the current source under test and running an AC analysis with respect to the voltage source. A plot is then obtained of the ratio of the voltage to the current at the current source's output. The temptation to use an ideal independent current source to provide the test stimulus should be resisted; this is because an ideal current source possesses infinite output impedance and would, therefore, severely load the current source under test, giving erroneous results.

The increase in loop gain occasioned by amplification in common emitter control transistor **Q2** gives the ANF current source more than ten times the output impedance at 100Hz (**fig. 3**) of the voltage-reference-biased current source of **figure 2** where no amplification of the feedback signal occurs. This result is confirmed by Camenzind [1] and is contrary to Jung's counter-intuitive assertion [2] that the output impedance of the voltage-reference-biased current source of **figure 2** is superior to that of the ANF current source; indeed, the output impedance of the ANF current source is on a par with that of a cascode current source, being of the order of tens of mega-ohms rather than the tens of kilo-ohms suggested by Jung.

Jung assumes that a current source's output impedance can be inferred from its power supply rejection ratio (PSRR), but this is incorrect precisely because the PSRR of the current sources of **figure 1** and **figure 2** is as much a function of their appurtenant biasing and decoupling components, if any, as their output impedance. For example, the PSRR of a current source can be increased independently and significantly, irrespective of its output impedance, by splitting its bias resistor into two halves and decoupling the midpoint of the two resistors to the supply rail (**fig. 4**) [3].

Note that although the advantage with respect to output impedance that the ANF current source possesses over the voltage-reference-biased current source typically extends across the audio band with most small signal transistors, this advantage disappears at ultrasonic frequencies. The output impedance of both current sources, and, indeed, all practical discrete-transistor current sources, drops at a single pole rate at high frequencies, and this is due to parasitic capacitance to ground at the output (collector) of each current source.

Jung also maintains [2] that the ANF current source is prone to oscillation if high bandwidth transistors are used in its construction; he recommends the inclusion of a small ($\sim 100\ \Omega$) resistor **R3** in series with the base of the control transistor's base to eliminate such oscillation (**fig. 5**). To quantify the effect of this resistor on loop transmission, the ANF current source's feedback loop stability margins were evaluated with loop gain probes in LTspice. The loop gain probes may be inserted in series with the base of the control transistor (**fig. 5**) or in series with the base of the current source transistor.

Depending on the current gain of the small signal transistors used, the ANF current source possesses 40dB–60dB loop gain or loop transmission at 100Hz. This relatively low loop gain, coupled with the low number and wide spacing of the feedback loop's singularities, would appear to preclude the possibility of instability. Nevertheless loop gain analysis (**fig. 6**) indicates that the control transistor's base resistor improves loop gain stability margins by lowering the frequency of the dominant loop transmission pole which now comprises the input capacitance of the control transistor and its base resistor.

Loop gain analysis in LTspice also reveals that the value of the control transistor's base resistor **R3** should be of the order of 1Kilo-ohm to effect a significant improvement in stability margins (**fig. 6**). If even greater margins of stability are required, then a zero can, in principal, be introduced in the vicinity of the unity loop gain frequency by connecting a small ($\sim 10\text{pF}$) capacitor in parallel with the control transistor's base resistor. Regrettably this zero cannot be placed with an adequate degree of accuracy in practice because the input capacitance of the control transistor, and, therefore, the location of the unity loop gain frequency, is unknown and, moreover, varies widely from one transistor specimen to another.

Increased freedom from unreliable transistor parameters may be obtained by using dominant pole-zero shunt compensation at the collector of the control transistor **Q2** of the ANF current source (**fig. 7**); the shunt compensation network comprises capacitor **C1** and resistor **R3** connected between the collector of the control transistor **Q2** and the supply rail, which is effectively at ground potential at the frequencies of interest. Capacitor **C1** lowers the frequency of the dominant loop transmission pole, while the small series resistor **R3** introduces a zero in the vicinity of the unity loop gain frequency, improving phase margin from 28 degrees, without the compensation network, to 130 degrees (**fig. 8**); these singularities remain largely invariant, irrespective of the small signal transistors used, assuming the value of the control transistor's collector load resistor **R2** remains constant. For values of the control transistor's collector load resistor **R2** in the range 10Kilo-ohm–22Kilo-ohm, the values of the shunt compensation network's capacitor **C1** and resistor **R3** need not exceed 3.3nF and 10 Ohms respectively.

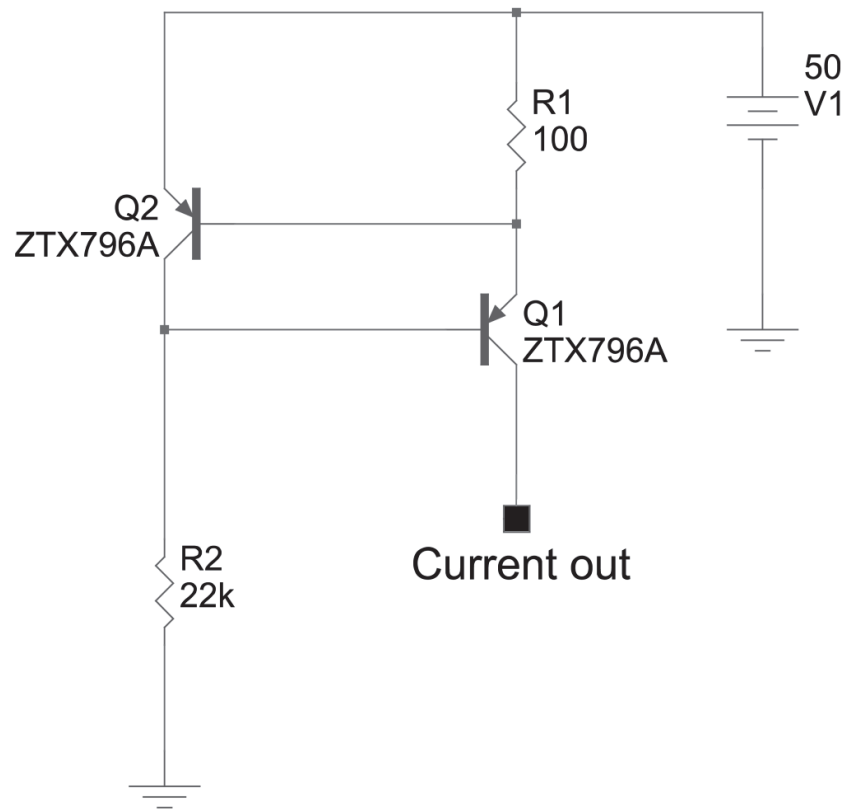


Figure 1. The amplified negative feedback current source.

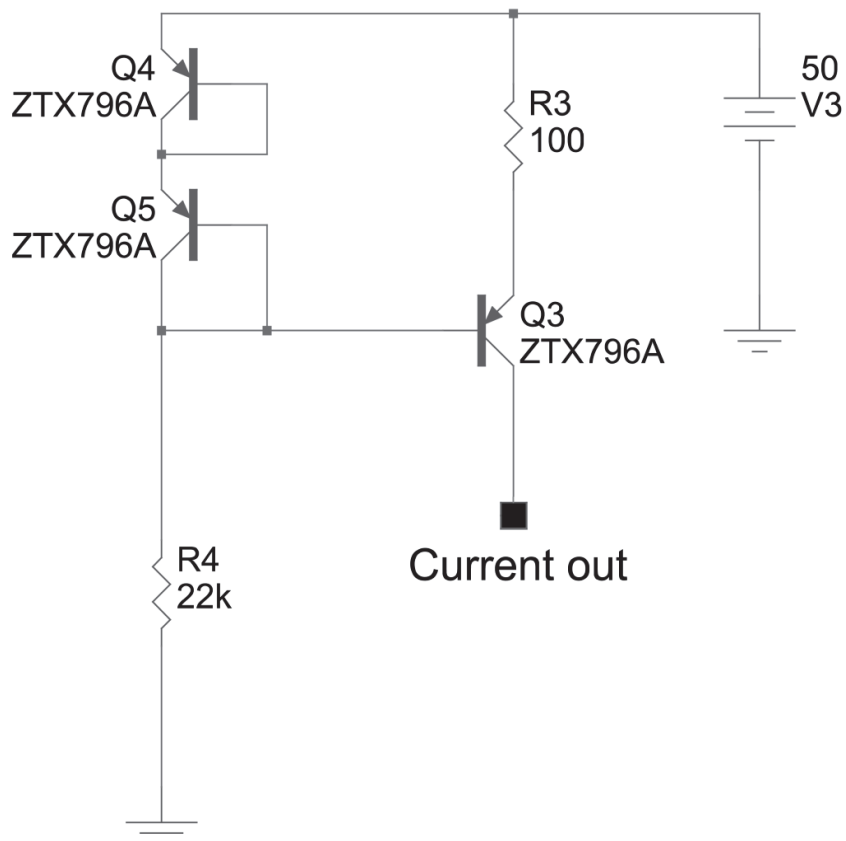


Figure 2. Voltage-reference-biased current source.

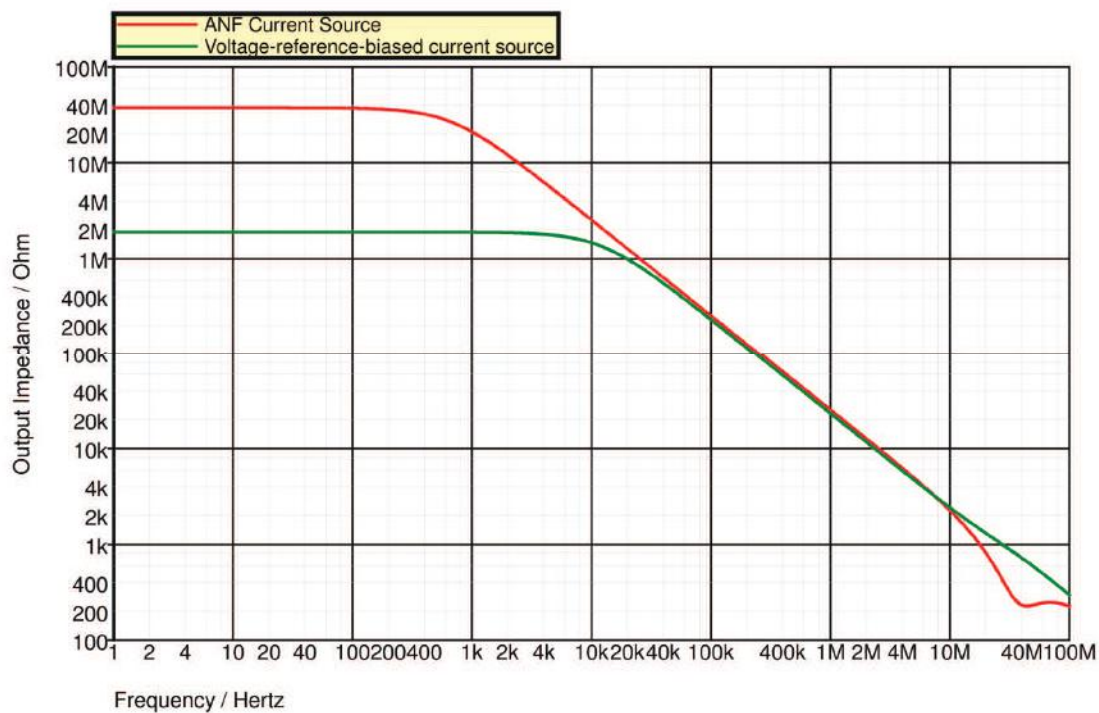


Figure 3. The output impedance of the ANF current source is superior to that of the voltage-reference-biased current source across the audio band.

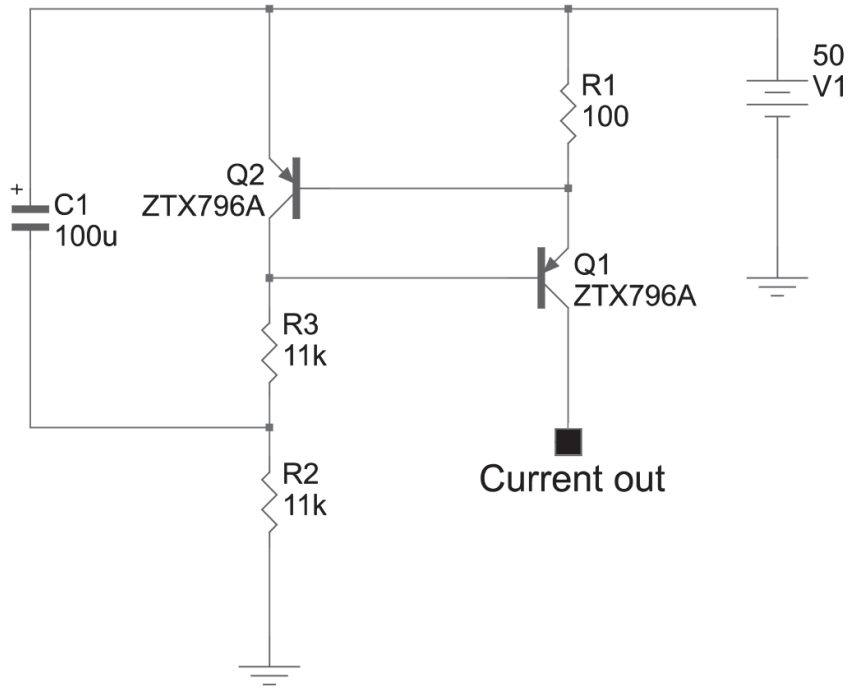


Figure 4. AC-decoupling the midpoint of bias resistors R2 and R3 increases the PSRR of the current source irrespective of its output impedance.

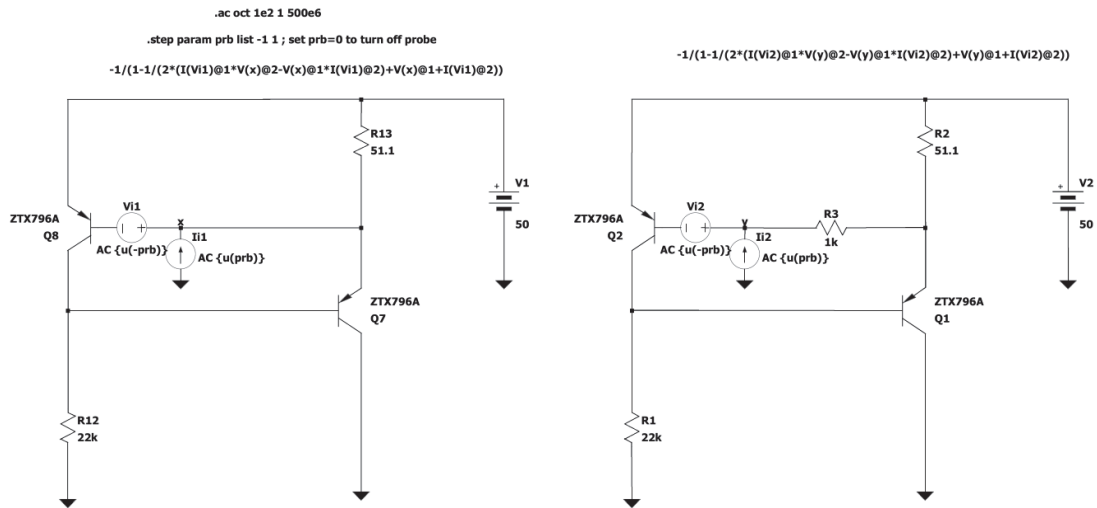


Figure 5. The loop gain probes are inserted in series with the base of the control transistors to obtain plots of loop transmission with frequency with and without a 1 kilo-ohm resistor in series with the base of the control transistors Q2 and Q8 respectively.

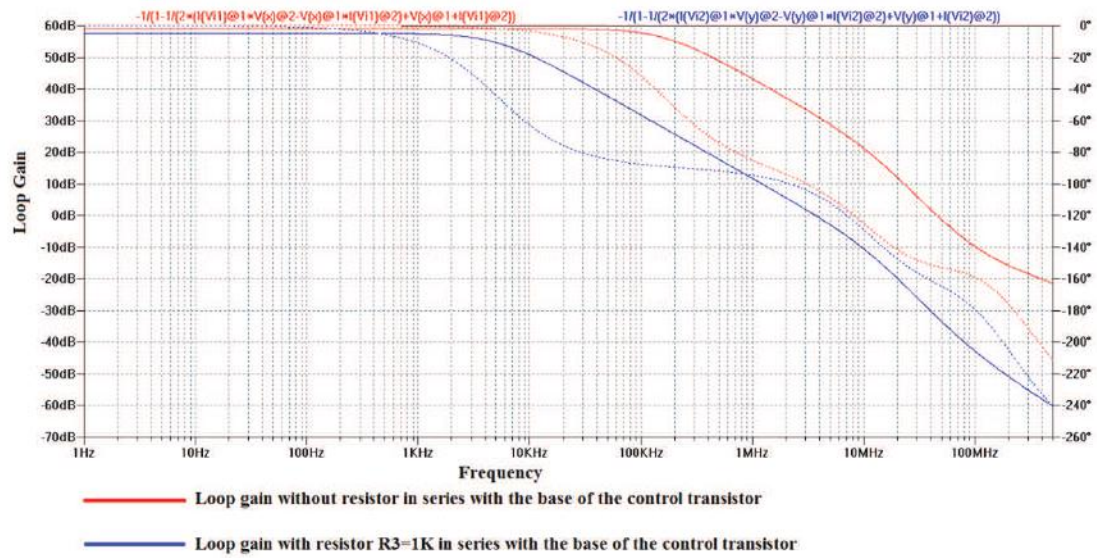


Figure 6. Phase margin improves from 28 degrees without a resistor in series with the base of the control transistor to 74 degrees with the 1K resistor in situ.

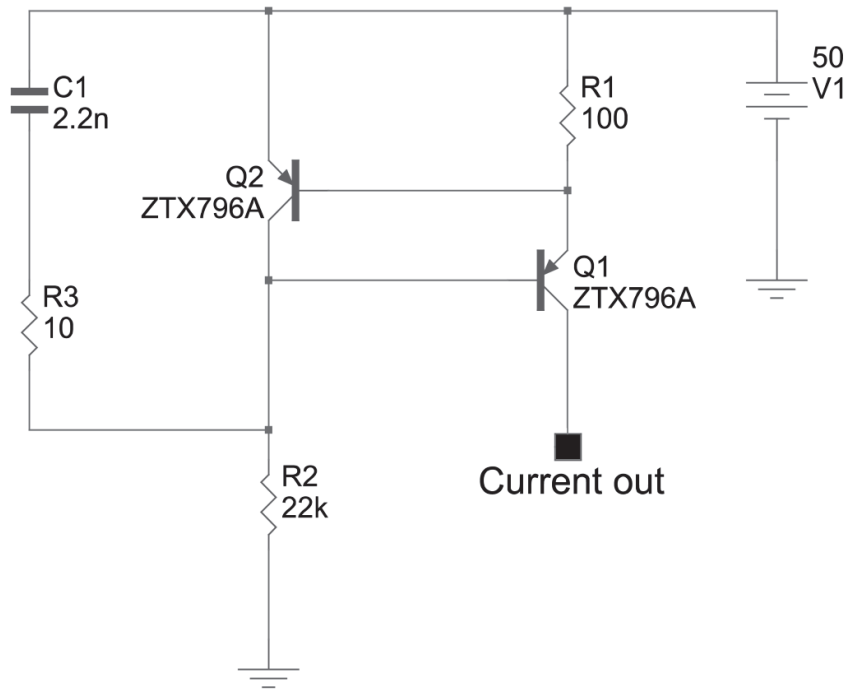


Figure 7. The pole-zero shunt compensation network, comprising R3 and C1, allows relatively accurate placement of the unity loop gain zero.

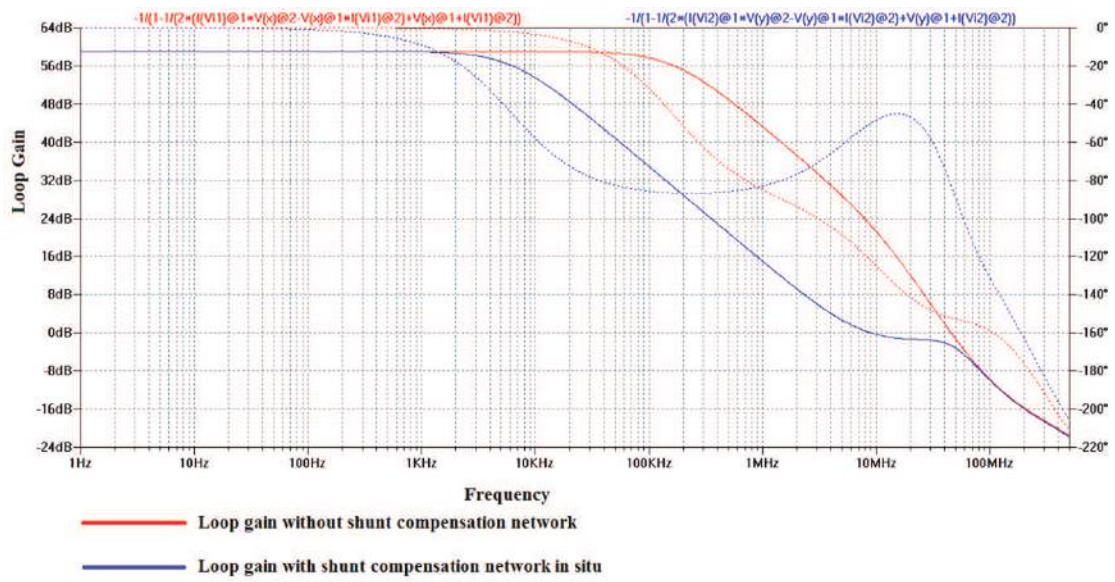


Figure 8. Shunt compensation network increases phase margin from 28 degrees to 130 degrees.

The ANF Voltage Source

An ANF current source is easily converted into a low-impedance amplified negative feedback voltage source by inserting a suitable voltage reference **D1** between the emitter of transistor **Q1** and resistor **R1** (**fig. 9**). As previously noted the voltage reference can be a series of diodes, an LED or a zener diode. The voltage reference **D1** is supplied with a constant current, which is largely immune to supply rail variations, by resistor **R1**. The voltage output is taken from the emitter of transistor **Q1**. Resistor **R3** increases stability margins of the feedback loop; alternatively, as previously demonstrated, pole-zero shunt compensation from the collector of the control transistor **Q2** may be used to accomplish this objective.

The ANF voltage source possesses the advantage that if the voltage reference **D1** is a zener diode with a positive temperature coefficient of approximately 2.2mv/degree Celsius, then this positive temperature coefficient is compensated for by the negative (~2.2mv/degree Celsius) of the base-emitter voltage of control transistor **Q2**; this gives good stability of output voltage over a wide temperature range.

The variation of the ANF voltage source's output impedance with frequency is shown in **figure 10**. This plot was obtained by connecting a grounded ideal independent current source to the output of the ANF voltage source and running an AC analysis with respect to the ideal current source. The output impedance is then merely the ratio of the output voltage to the current delivered by the ideal current test source. The test source needs to be a current source and not a voltage source because the circuit under test is a nominal voltage source which, therefore, requires a test source with an infinite output impedance to prevent erroneous results being obtained due to the loading of the test source on the circuit under test.

The output impedance of the ANF voltage source is inductive, being of the order of tens of milliohms across the audio band before increasing sharply at ultrasonic frequencies (**fig. 10**). To prevent this rise in output impedance, shunt capacitor **C1** to ground is connected across the ANF voltage source's output (**fig. 9**); capacitor **C1** should be at least 47uF to be effective, as the plot of **figure 10** reveals.

Capacitor **C2** prevents power supply ripple from significantly disrupting the feedback loop; in other words, capacitor **C2** improves the power supply rejection ratio (PSRR) of the ANF voltage source. To obtain the circuit's PSRR with frequency, an ideal AC voltage source was connected in series with the DC voltage source **V1** energising the circuit. The frequency response (effectively the PSRR) with respect to the output of the ANF voltage source was then obtained (**fig. 11**). Capacitor **C2** improves the PSRR of the ANF voltage source by nearly 50 dB (to over 110dB) at the ripple frequency of 100Hz. The decrease in PSRR beyond 1kHz and with **C2** in situ is due to ripple injection through the collector of transistor **Q1**, while the increase in PSRR beyond 80 KHz is due to capacitor **C1** shunting the output.

The ANF voltage source may, for example, be used as a low-impedance voltage source to bias the current sources of the transadmittance stage (TAS) and the transimpedance stage (TIS) in the amplifier of the form shown in **figure 12**. This marginally reduces the component count compared with using two separate ANF current sources, but it compromises performance, at least in principal, because, as previously noted, the output impedance of each of the current sources is now less than one tenth, at 100Hz, of that which would be obtained if wholly independent ANF current sources were used to bias the TAS and the TIS.

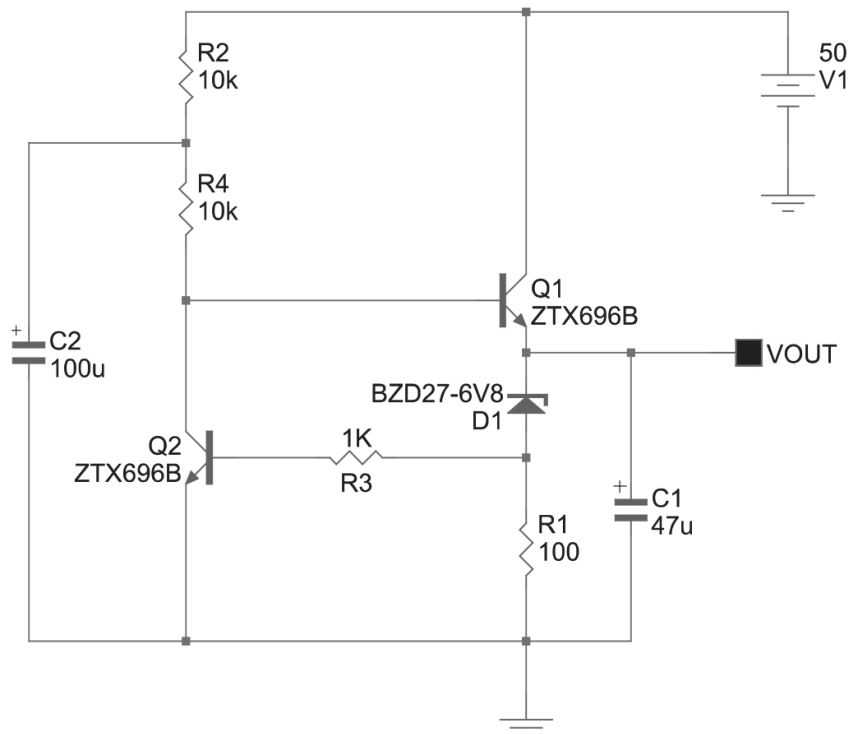


Figure 9. The amplified negative feedback voltage source.

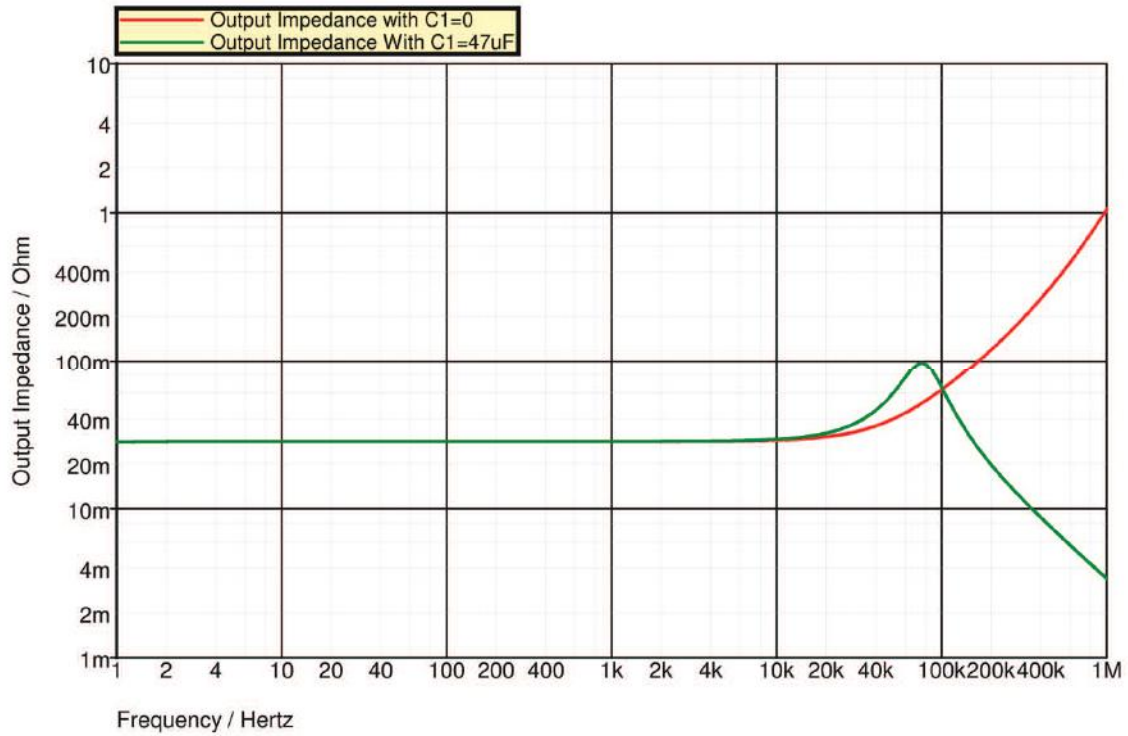


Figure 10. The output impedance of the ANF voltage source is inductive in the absence of output shunt capacitor C1.

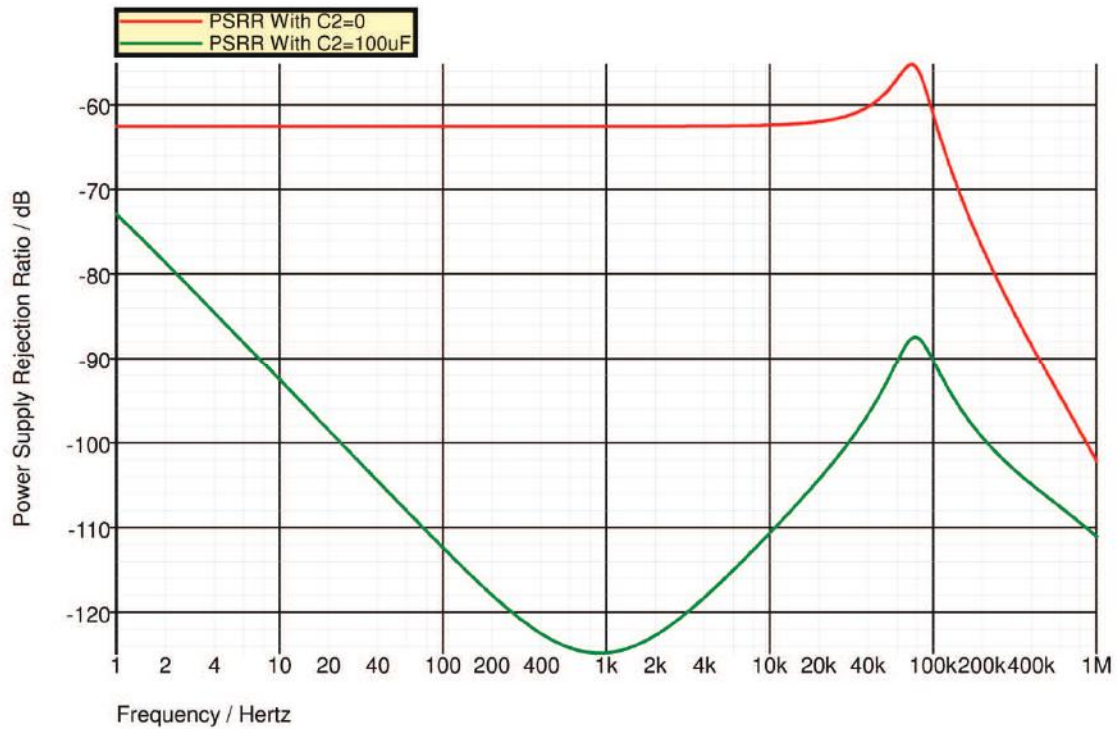


Figure 11. Decoupling capacitor C2 improves PSRR of the ANF voltage source by nearly 50dB (to over 110dB) at the ripple frequency of 100Hz.

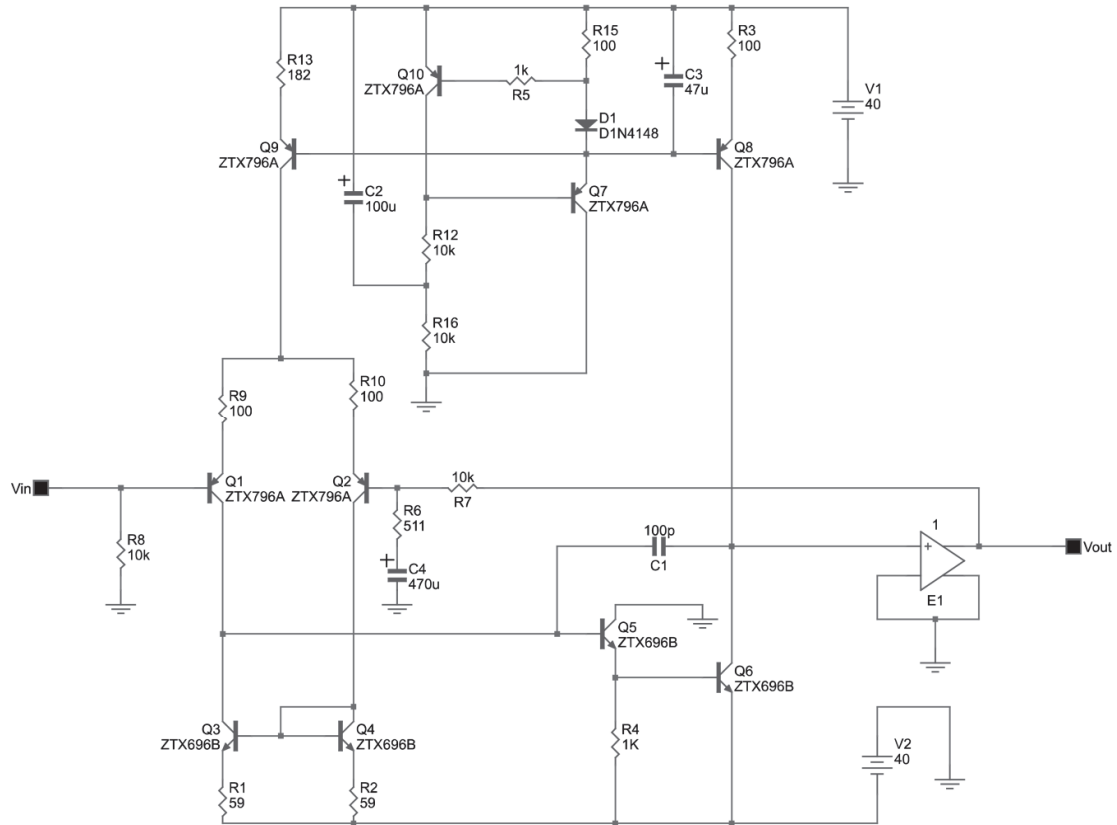


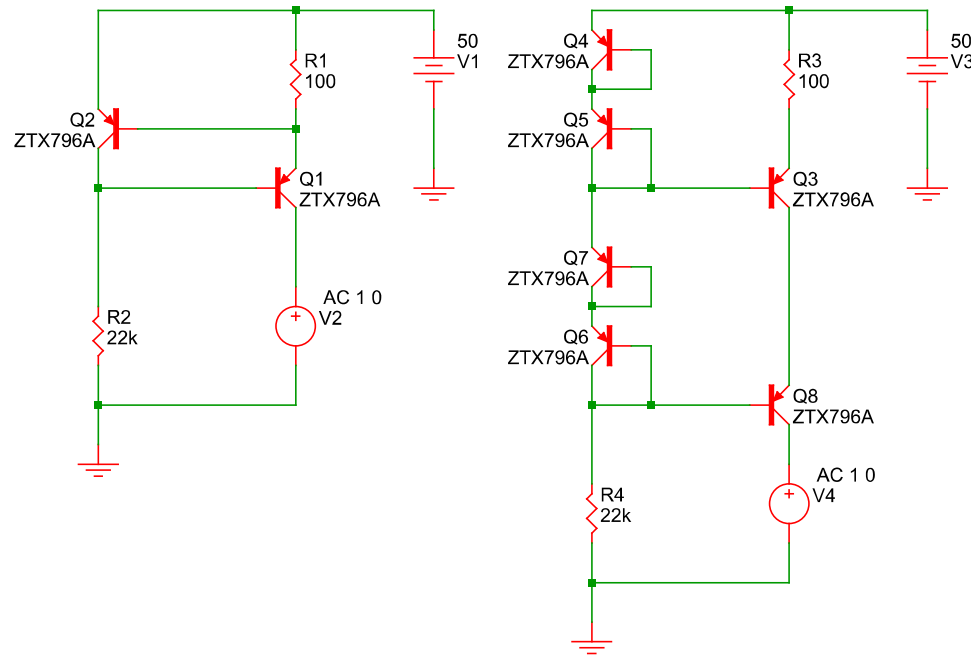
Figure 12. The rudiments of an amplifier of the Thompson topology whose current sources are biased by a single ANF voltage source. The input stage is a transadmittance stage (TAS) while the second stage is a transimpedance stage (TIS); the unity-gain voltage-controlled voltage source E1 represents the output stage of the amplifier.

Conclusion

The ANF current source is a simple and versatile circuit whose output impedance greatly surpasses that of virtually all forms of discrete-transistor voltage-reference-biased current sources across the audio band. In fact, the ANF current source's output impedance is of the same order as that of a cascode current source, with the additional advantage that it functions with a significantly smaller voltage drop across it (the compliance voltage) than the cascode current source; it also possesses a much smaller component count compared with the cascode current source. The versatility of the ANF current source is underscored by the fact that it can be modified to function as a low-impedance voltage source. Given its low cost, it is difficult to conceive of any reason not to use the ANF current source exclusively where a current source is called for in the design of discrete audio frequency amplifiers.

References

1. Camenzind, H., “Designing Analog Chips”, Chapter 5. Available at http://www.designinganalogchips.com/_count/designinganalogchips.pdf
2. Jung, W., “Sources 101: Audio Current Regulator Tests for High Performance Part 1: Basics of Operation.” Audioexpress, April 2007. pg 1~10.
3. Crecraft, D. I., et al, “Electronics”. Chapman & Hall, ISBN 0-412-41320-5, pg 566.



ANF and Cascode Current Source Output Impedance

