

# High Performance Audio Stages Using Transimpedance Amplifiers

by Walt Jung

Transimpedance or current feedback amplifiers are still relatively new to audio applications, since they are primarily designed for video circuits. While the AD846 (an early high-performance example) was successfully used in TAA,<sup>1</sup> transimpedance amps may not be completely familiar devices (The AD846 data sheet contains a detailed discussion of transimpedance amplifier theory). Interestingly, they possess several performance attributes quite useful in audio circuits. Among their virtues are very high slew rate and bandwidth, high output current, and the ability to drive low impedance loads with excellent linearity. Because of these factors, more designers and audiophiles will use them.

Viewed from the exterior of an application, a circuit using a transimpedance amp can be deceiving. It can look just like one using a more conventional op amp. Both transimpedance amps and conventional (voltage input) op amps use a common symbol, and are often called op amps. Nevertheless, their behavior can often be quite different.

The simplified gain expression for a non-inverting voltage-gain stage based on a transimpedance amp is similar to one using a conventional voltage input op amp. This gain "G" is expressed as:

$$G = 1 + (R_F/R_{IN}) \quad (1)$$

Similarly, a current-to-voltage (I/V) converter using a transimpedance amp is like using a voltage input op amp counterpart, where the output voltage "V" is:

$$V = - (I_{IN})(R_F) \quad (2)$$

What these two expressions don't show is that the feedback resistor  $R_F$  cannot be chosen freely with a transimpedance amplifier (as we know, it can be with the more familiar voltage input amplifier). This is because  $R_F$  used in a transimpedance amplifier serves also as an element of the frequency compensation, along with an internal capacitor ( $C_C$ ). As a result, the gain of such a stage must be set via  $R_{IN}$  when using a transimpedance amplifier, with  $R_F$  a fixed value unique to a given amplifier type.

Usually,  $R_F$  is optimized at the specific value which maximizes am-

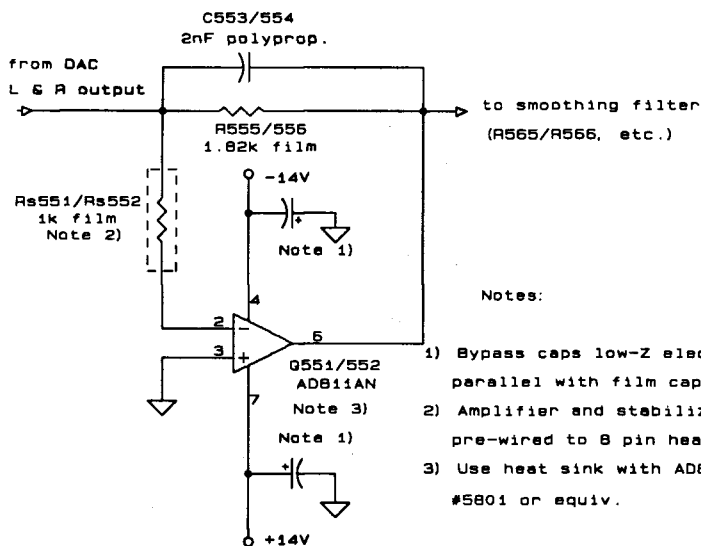
plifier bandwidth, typically this is around 1k $\Omega$ . While the designer has some limited freedom to vary  $R_F$  by a small percentage, it will be at the expense of bandwidth variation (a higher  $R_F$  value yields less bandwidth; a lower value more). Some minimum value for  $R_F$  must always be present in the feedback path for transimpedance amplifier stability. This necessarily impacts applications beyond the case of the straight voltage-gain stage above, where the unique stability criteria for  $R_F$  is almost transparent.

For example, while a conventional op-amp voltage follower can use a directly wired feedback connection from output to inverting input, a transimpedance-amp voltage follower must use the specified value of  $R_F$  for the given device. To use the example cited, a 1k $\Omega$  resistor from output to inverting input. This produces a transimpedance amp version of a voltage follower (more on this in the line stage example).

Because of the fundamental necessity for this frequency compensation resistor, it has been stated that transimpedance amps cannot be used in integrating I/V stages,<sup>2</sup> such as the first analog stage of virtually all Philips-family CD playback devices. This interface to the DAC is an integrating I/V converter, forming the first section of a three-pole low-pass filter. While it is certainly true that one cannot simply drop a transimpedance amp into an integrator designed for a conventional op amp, it is not true that integrators cannot be made using transimpedance amps. Like the voltage follower, feedback can be effectively 100%, as long as a minimum  $R_F$  value is present in the circuit for stability.

Figure A is a case in point, and shows what is a basic first stage of the classic Philips I/V conversion topology, an integrating I/V stage (de-emphasis circuitry not shown). When used with a conventional op amp, stabilization resistor  $R_S$  is not present, and this circuit forms the first filter pole of a three-pole Bessel rolloff as well as I/V conversion. The I/V conversion gain is set by the value of  $R_{555}$  and the DAC current output. The location of the first pole is set by the

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Notes:

- 1) Bypass caps low-Z electrolytics in parallel with film caps.
- 2) Amplifier and stabilization resistor pre-wired to 8 pin header.
- 3) Use heat sink with ADB11AN. Aavid #5801 or equiv.

FIGURE A: A transimpedance amplifier integrating I/V.

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time constant R555-C553 (3.64 $\mu$ s as shown), producing a corner frequency of 43.7kHz.

With a transimpedance amp used for the Q551 amplifier function, stability is provided by Rs551, using a value appropriate to the device and bandwidth desired. This technique was previously described in the OP160 data sheet, specifically as an integrator.<sup>3</sup> In the circuit here, the main signal path is still from the DAC and through R555/C553, while Rs551 carries the input error current to the transimpedance amplifier

Q551. In essence, Rs551 is performing the frequency compensation function, analogous in that sense to the classical connection of R<sub>f</sub>. Some performance figures with a high-grade transimpedance amplifier will serve to place the operation of this stage in perspective.

As connected here, and using an AD811 transimpedance amp,<sup>4</sup> this circuit constitutes a voltage input op amp, as seen at the top of Rs551 (the I/V converter's summing junction). The gain of a transimpedance amp is defined by its transresistance, R<sub>T</sub> (that's where the name comes from).

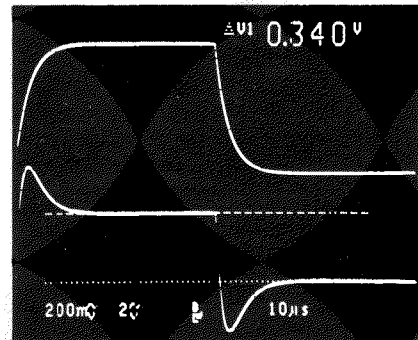


PHOTO A: Bench test of integrating I/V. V<sub>1</sub> (bottom) = error voltage  $\times$  100 v<sub>2</sub> (top) = Integrator output (10kHz square wave source).

The AD811 has a (loaded) R<sub>T</sub> of 1.5M, so the net voltage gain from the summing point to the output is the ratio R<sub>T</sub>/Rs551, or 1.5E6/1E3 = 1500/1 (or, in dB, 63.5dB). For a 6V p-p output signal from Q551, the input summing point error required to drive the Rs551/Q551 loop should be under 6mV p-p, a figure well below the recommended 25mV p-p compliance of the TDA1541 DAC family. This point in general can be a critical one, as most current output DACs have small compliance voltages for a specified linearity.

The open loop bandwidth of the AD811 is determined by R<sub>T</sub> and C<sub>c</sub> as:

$$f_{(OL)} = 1 / (2 \times \pi \times R_T \times C_c) \quad (3)$$

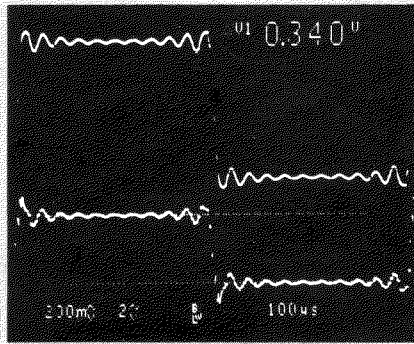


PHOTO B: CD playback test of integrating I/V  $V_1$  (bottom) = error voltage  $\times 100$ ,  $V_2$  (top) = Integrator output (1kHz 0dB test disc source).

For 1.5M and 5pF, this works out to be about 21kHz, very nicely accommodating the CD bandwidth.

### A Dynamic I/V Test

To better illustrate how this transimpedance amplifier performs as an integrating I/V converter, some bench and CD playback tests we conducted as a demonstration, and are shown in Photos A-C.

Photo A shows the I/V stage of Fig. A in a bench test, driven from a 0-4mA current source, which simulates the DAC being exercised with a full-scale step signal. This signal constitutes worst case conditions for the I/V in this CD application, both in amplitude and speed. Overload will

show up as an abrupt change in the error voltage, which is  $V_1$ , the bottom trace. The output of the I/V stage is  $V_2$ , the top trace. For these measurements, a  $100\times$  gain 8-pin instrumentation amplifier (AD620) was used to amplify the error at the summing point, "piggybacked" on the AD811. Thus the " $V_1$ " voltages in the photos are divided by 100 to reflect actual input error. For reference, the AD620 has a small signal bandwidth of over 100kHz for this test, and a slew rate of  $1.2V/\mu s$ .

Photo A shows a baseline error of 3.4mV p-p, rising somewhat higher with signal transitions. This is consistent with the calculated gain of the AD811 as it is used here, and clearly there is no overload. The 3.4mV p-p error for a 4mA p-p signal current suggests that the dynamic impedance of this I/V terminating the DAC is  $3.4E-3/4E-3 = 0.85\Omega$ , or generally on the order of  $1\Omega$  or less. The dynamic voltage change of 5mV or less is useful in minimizing voltage compliance related errors, when used with any current DAC.

Photo B shows the same I/V stage operating in an actual CD I/V converter, with exactly the same scope amplitude settings. The signal source is a 1002.27Hz square wave CD track, at 0dB amplitude.<sup>5</sup> Interestingly, the dynamic error voltage is exactly the same for the same output. Also, the large signal rate of change shown for this test is actually lower than the bench test of Photo A (therefore the

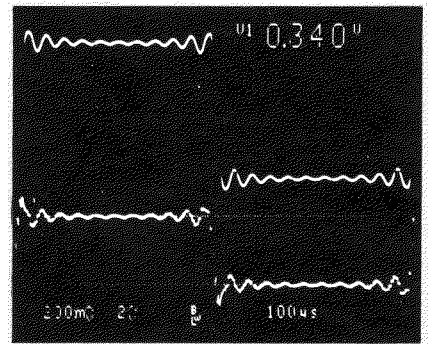


PHOTO C: CD playback test of integrating I/V  $V_1$  (bottom) = error voltage  $\times 100$ ,  $V_2$  (top) = CD Player output (after filtering) (1kHz 0dB test disc source).

bench test is more rigorous in this regard).

Some small amplitude DAC steps are noted on these signals, and are shown more completely smoothed in waveform  $V_2$  of Photo C, the final output of the CD player after traversing all three poles of filtering.

We also bench tested the AD846 with interesting results (not shown). It revealed extremely small low frequency errors of only a few tens of microvolts, while the error on transitions is 2-3 times larger than the AD811. With the AD846 this would generally be expected from the relatively higher  $R_T$ , and the relatively lower bandwidth and slew rate, vis-a-vis the AD811.

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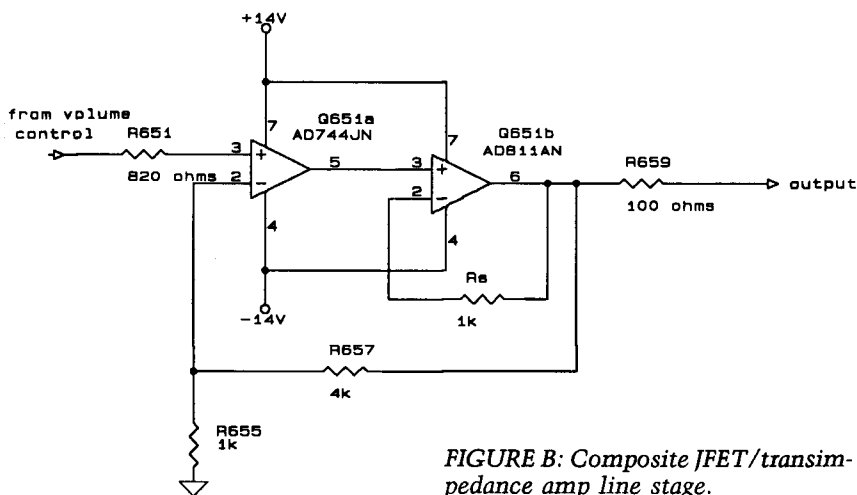


FIGURE B: Composite JFET/transimpedance amp line stage.

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### A Transimpedance Amp Line Stage

The above discussion has been a somewhat special case for audio applications, since I/V conversion is unique to digital audio uses. A circuit more broad in terms of application is a flat wideband line stage, such as the circuit of Fig. B.

This circuit is a wideband amplifier with an overall gain of five times, set by R657 and R655 (as in the equation). The difference in this case is that the overall amplifier is composed of both

Q651a and Q651b, with each optimized for their specific input/output functions.<sup>6</sup> Q651a, a low-distortion AD744 JFET input op amp, provides low input current and a very high loading impedance, allowing direct coupling to the signal source. This will normally be a pot in the range of 10–50k $\Omega$ , which is desirably very lightly loaded.

Since transimpedance amplifiers typically have input bias currents of about  $\pm 1\mu\text{A}$ , they don't serve well used with relatively high source impedances (higher than 1k $\Omega$ ). Thus the

JFET amplifier is optimum as an input interface, while Q651b (an AD811AN transimpedance amp) provides an ample load drive of more than 100mA. As you can see, Q651b is connected as a transimpedance amp unity gain follower, with the 1k $\Omega$   $R_S$  serving as the frequency compensation resistor.

In this case, the overall composite connection of the AD744JN and the AD811AN work very well together, and the net distortion is quite low, on the order of  $-100\text{dB}$  for several volts of output. As with the I/V circuit, heat sinking of the AD811AN is recommended for supplies above  $\pm 12\text{V}$ , and the power supplies of this composite line amp should be well bypassed.

### REFERENCES

1. Marchese, P., "High Performance Analog Circuitry for CD Players," *TAA*, 2/90, p. 8.
2. Rich, D., "A Brief Update on CD Players," *The Audio Critic*, #16, 1991, pp. 49–50.
3. "Analog Devices OP160 Data Sheet," 5/90, p. 19.
4. Whitney, D., Jung, W., "Applying a High-Performance Video Operational Amplifier," *Analog Dialogue*, 26-1, 1992.
5. CBS CD-1 test disc, track 16.
6. Jung, W., Wurcer, S., "A High Performance Audio Composite Line Driver Stage," *Analog Devices Seminar Notes*, 1992.